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THE SECONDARY ENRICHMENT OF SILVER ORES

H. C. COOKE

INTRODUCTION

The past half-century has been a period of rapid development of mines and mining, both in America and in other countries, and as a consequence, the basal facts regarding the occurrence of ores are now comparatively well understood. The geologic causes for the location of ore-bodies in certain zones or horizons are in many cases known, and many former theories are generally accepted as facts. The transportation of ores by aqueous solutions, the origin of some of these solutions in cooling igneous magmas, and the secondary enrichment of many ore-bodies through the agency of meteoric waters; such are some of the ideas which have withstood prolonged criticism and have become established tenets of geologic faith. But beyond basal facts, adduced almost solely from field evidence, our knowledge of the mechanism of ore depositions is somewhat vague and unsatisfactory. Only prolonged investigation along chemical and physico-chemical lines will render possible a reasonably accurate understanding of the complex composition of ore-bearing solutions, of the reactions of these solutions with the wall rocks, of the causes for the deposition of minerals from them, and of many other problems connected with the deposition of ores.

At the present time the problems most important and most

amenable to solution are those of secondary enrichment; most important, because many of the most valuable deposits were concentrated in this way; most amenable to treatment, because many of the factors of the problems are known, i.e., temperature, pressure, concentrations of solutions, and the chemical nature of the reacting solutions and of the minerals affected.

The principles of secondary enrichment have been outlined by Penrose,[1] S. F. Emmons,[2] Weed,[3] Van Hise,[4] Lindgren,[5] and others, and confirmed by the work of many investigators. In a few cases the chemical reactions which take place have been studied in some detail. Brokaw[6] and McCaughey[7] have investigated the solution of gold in surface waters; Van Hise,[8] Leith, and their associates at the University of Wisconsin have studied the deposition and enrichment of the Lake Superior iron ores; Gottschalk and Buehler[9] have shown the reactions by which the sulphides of iron, lead, zinc, and other metals are taken into solution; and Allen[10] has precipitated pyrite and marcasite under natural conditions.

The processes of the secondary enrichment of silver are of much interest both because they are of widespread occurrence and because a relatively small amount of secondary enrichment may render a low-grade deposit commercially profitable. There is a great variety of secondary silver minerals, and some of them may be deposited even at considerable depths. The mechanism of this downward migration has been discussed by many writers. Near the surface, some have supposed, the silver was dissolved by sulphate solutions, others have regarded chloride waters as increasing

[1] Penrose, "Superficial Alteration of Ore Deposits," *Jour. Geol.*, II (1904), 288.

[2] S. F. Emmons, "The Secondary Enrichment of Ore Deposits," *Trans. A.I.M.E.*, XXX (1900), 177.

[3] Weed, "The Enrichment of Gold and Silver Veins," *ibid.*, p. 424.

[4] Van Hise, "Some Principles Controlling the Deposition of Ores," *ibid.*, p. 27.

[5] Lindgren, "Copper Deposits of the Clifton Morenci District," *U.S.G.S.*, XLIII (1905), 177.

[6] Brokaw, *Journal of Geology*, XVIII (1910), 321.

[7] McCaughey, *Jour. Am. Chem. Soc.*, XXXI (1909), 1263.

[8] Van Hise and Leith, *U.S.G.S. Monograph* 52 (1911).

[9] Gottschalk and Buehler, *Economic Geology*, VII (1912), 15.

[10] Allen, *Am. Jour. Sci.* (4), XXXIII (1912), 169.

the solubility, and still others have assumed the agency of carbonate waters. At greater depths, the precipitation has been thought to be due to the action of hydrogen sulphide or of other sulphides, to the reduction of sulphate solutions by organic matter, or to other causes. The work described in this paper was undertaken to test some of the hypotheses mentioned and to discover if possible in the laboratory the actual extent and speed of the reactions that were found to take place. While much remains to be done, the results herein presented are such as to indicate with some degree of certainty the probable reactions which take place in the solution of silver ores by meteoric waters, and, to a less extent, those which occur in their precipitation.

DEFINITION OF TERMS

The terms "primary" and "secondary" have not always been employed with precise meaning and their use is likely to be attended with some confusion. Wherever introduced into this paper, they are used in a genetic sense. Unless otherwise indicated, the term "primary" implies the agency of hot ascending waters; "secondary," that of cold meteoric waters. It is commonly recognized that some silver ores have been deposited by the agency of cold sulphate solutions in rocks devoid of sulphides.[1] Such deposits might be termed primary, but in their chemical aspects they are secondary, since they differ from those which ordinarily would be termed secondary only in the distance the silver solutions have been carried and in that they have been deposited outside of some zone of primary minerals. As regards their origin through the solution of some truly primary silver mineral, their method of transportation in solution, and the methods of their precipitation, they do not differ from ores precipitated in a silver lode after having been transported a short distance.

SCOPE OF THE DISCUSSION

A study of the literature of silver deposits brings out the fact that all of the silver minerals except the chloride may have either a primary or a secondary origin. These minerals include, in addi

[1] W. H. Emmons, "The Cashin Mine, Montrose Co., Colo.," *U.S.G.S. Bull.* 285 (1905), 125.

tion to compounds of silver with a single acid element, many double compounds, particularly with arsenic, antimony, and tellurium. Argentiferous galena and tetrahedrite are likewise very common sources of silver. Since a description of the secondary enrichment of any metal must account fully for the processes of its solution in meteoric waters, its transportation by, and its precipitation from, them, a complete study of the processes of the secondary enrichment of silver must involve also an explanation of the migration of the sulphides of lead, copper, arsenic, and antimony, in the same ground-waters that carry silver.

PREVIOUS WORK—EXPERIMENTAL

Experimental data bearing on this problem are few, since those who have touched the question in the laboratory have rarely worked under the conditions which commonly obtain in secondarily enriched ore deposits; i.e., low temperatures, small concentrations, low pressures, and a somewhat narrow range of possibilities in the way of chemical composition. Johnston[1] showed that silver carbonate will dissolve in water saturated with carbon dioxide at 15° C. to the extent of 0.846 gm. per liter. Senarmont[2] and Rickard[3] have demonstrated that native silver may be precipitated from silver solutions by organic or carbonaceous matter. Van Hise[4] states that silver sulphide is soluble in solutions of alkaline carbonates, but the writer has been unable to find reference to any experimental confirmation of this statement.

A few experiments have also been made under conditions within the range of possibility as to composition, though not as to temperature and pressure. Spring[5] showed that at pressures of 6,500 atmospheres silver sulphide was formed from its elements. Moesta[6] obtained metallic silver by passing steam at 100 C. over silver sul-

[1] G. S. Johnston, *Chem. N.*, LIV (1886), 75.

[2] Senarmont, *Annales Chim. Phys.*, 3d ser., XXXII (1851), 140.

[3] Rickard, *Trans. A.I.M.E.*, XXVI (1896), 978.

[4] Van Hise, *U.S.G.S. Monograph* 47 (1904), 1099.

[5] Spring, *Ber. Deutsch. Chem. Gesell.*, XVI, 324, 1002; XVII, 1218.

[6] Moesta, F. A., *Über das Vorkommen der Chlor-, Brom-, und Jodverbindungen des Silvers in der Natur; ein Beitrag zur Kenntn. d. geol. u. bergbaulichen Verhältnisse von Nord-Chile.* Marburg, 1870.

phide, and Plattner[1] obtained it by passing oxygen at 100° C.–120° C. over the same substance. Stokes[2] found that the reactions $Fe_2(SO_4)_3+2Ag=Ag_2SO_4+2FeSO_4$ and $2CuSO_4+2Ag=Cu_2SO_4+Ag_2SO_4$ were reversible; silver was dissolved on heating, and reprecipitated on cooling.

PREVIOUS WORK—FIELD DATA

Field data bearing on this problem are abundant so far as the paragenesis is concerned but few attempts have been made to discuss the problems in the light of chemical principles. The most suggestive contribution to the literature of the subject is by Weed.[3] He regards the presence of pyrite in silver lodes as prerequisite to the secondary enrichment of silver, and states that, in his experience, notable secondary enrichment has taken place only where there has been pyrite in abundance; where pyrite has not occurred in considerable amount, secondary concentration has not taken place even though all other conditions were favorable. If this relationship is true, then the solution of primary silver sulphides in meteoric waters must depend either (*a*) on the action on the silver minerals of the oxidation products of the pyrite, which may form according to the equations $FeS_2+7O+H_2O=FeSO_4+H_2SO_4$ and $2FeSO_4+H_2SO_4+O=Fe_2(SO_4)_3+H_2O$, or (*b*) on the direct oxidation of the silver minerals, due to the electrolytic action of the silver sulphide-pyrite couple, as recently described by Gottschalk and Buehler,[4] or (*c*) on a combination of these two actions.

In addition to the work of Weed, we have the evidence afforded by analyses of mine waters. While the waters collected from a mine may differ slightly in composition from the ground-waters that seeped through the undisturbed deposit, in that they are probably more dilute on account of the freer circulation of the solutions, and are also more highly oxidized on account of greater access to the atmosphere, yet nevertheless their composition approaches fairly closely that of the original ground-waters. The following tables include most of the complete analyses that have

[1] Plattner, C. F., *Die Metallurgischen Rostprocesse.* Freiberg, 1856.

[2] Stokes, *Economic Geology*, I (1906), 649.

[3] Weed, *Trans. A.I.M.E.*, XXX, 431. [4] *Op. cit.*

	1*	2*	3†	4†	5†	6†	7†
SO_4	43.2	161.7	380.38	474.0	209,100.0	173.4	272.3
Cl	7.9	186.4	1.27	19.0	127.6	0.52	13.77
CO_3	110.5	1513.4	115.0	20.5	Undetermined	47.7	241.4
SiO_2	25.9	24.4	30.5	133.4	616.0	37.8	59.9
K	10.6	198.0	8.4	53.4	......	62.26	80.9
Na	36.4	719.4	57.1	132.0	535.0	0.27	6.86
Ca	37.4	146.4	148.1	100.1	1,286.0	72.4	113.7
Mg	12.25	177.7	154.0	5.9	6,590.0	......	......
Al	0.4	1.0	......	1.37	9,670.0	......	......
Mn	0.8	0.6	......	......	885.0	......	......
Fe''	0.7	3.5	......	......	......	......	......
Fe'''				6.33	5,025.0		
Acidity	......	......	......	......	147.5	......	......
Cu	......	......	......	......	......	......	......

	8†	9‡	10‡	11§	12§	13§	14§
SO_4	160.0	7.7	7.8	258.4	26.55	280.1	124.8
Cl	16.82	3.16	3.1	Tr.	Tr.	Tr.	12.4
CO_3	194.7	141.8	146.6	......	.....	......	......
SiO_2	68.9	32.7	41.4	2.1	8.0	8.8	18.0
K	254.1	1.0	1.6	......	.....	......	......
Na	7.84	13.4	13.7	......	.....	......	......
Ca	84.08	33.6	44.35	90.76	72.48	106.2	46.4
Mg	......	5.7	3.35	13.1	14.9	17.1	14.5
Al	......	......	......	1.5	0.4	1.5	......
Mn	......	0.27	1.9	4.7	4.1	1.9	......
Fe''	......	......	......	......	.....	......	6.6
Fe'''	Tr.	......	......	4.7	6.3	4.7	......
Acidity	......	Alkaline	Alkaline	......	.....	......	......
Zn	......	......	......	2.8	47.4	18.88	8.9

	15‖	16‖	17¶	18**	Average
SO_4	60.12	104.4	2039.5	327.2	179.0, excluding 5 and 17
Cl	Tr.	1.6	8.16	35.6	7.7, excluding 2 and 5
CO_3	78.3	92.4	......	87.9	116.0, excluding 2, 5, 11–14, 17
SiO_2	32.25	23.2	43.8	64.8	38.6, excluding 5,
K	2.4	3.5	70.0	3.4	27.0, excluding 2, 5, 8, 11–14
Na	28.5	7.5	106.3	148.8	46.5, excluding 2, 5, 11–14
Ca	17.3	46.2	187.2	68.8	83.2, excluding 5
Mg	1.3	7.3	93.5	6.3	40.0, excluding 5–9
Al	......	......	3.12	......	1.5, excluding 3, 5–10, 14–16, 17
Mn	0.3	3.2	155.6	0.7	2.0, excluding 3–8, 14, 17, 18
Fe''	1.5	0.9	164.8	......	
Fe'''	......	......	......	0.7	
Acidity	Alkaline	Alkaline	......	......	
Zn	......	......	49.66	......	
Cu	......	......	......	77.05	

* S. F. Emmons, 17th *Ann. Rep. U.S.G.S.*, Part 2, p. 462.
† Reed, *Bull. Dept. Geol. U. of California*, 4, pp. 189 and 192.
‡ Lindgren, 17th *Ann. Rep. U.S.G.S.*, Part 2, p. 121.
§ Beck, *Nature of Ore Deposits*, Weed's translation, II, 377.
‖ W. H. Emmons, unpublished manuscripts.
¶ L. J. W. Jones, *Proc. Colo. Sci. Soc.*, VI (1897), 48.
** R. C. Wells.

been made of the waters of gold and silver mines. For them the writer is indebted to Professor W. H. Emmons who has very kindly placed at his disposal the data which he is about to publish concerning secondary enrichment. The figures given are in parts per million.

1. Geyser silver mine, Custer Co., Colo., 500-foot level.
2. Same, 2,000-foot level.
3. Comstock lode, Savage mine, 600-foot level.
4. Comstock lode, G. and C. shaft, 2,250-foot level.
5. Comstock lode, Comstock mine, vadose water.
6. Comstock lode, Gould and Curry mine, 1,700-foot level.
7. Comstock lode, Hale and Norcross mine.
8. Comstock lode, Gould and Curry mine, 1,800-foot level.
9. Nevada City, Cal., Federal Loan mine, 400-foot level.
10. Nevada City, Cal., Black Prince mine, 400-foot level.

11–14. Rothschonberger Stolln, Freiberg, Germany.

15. Creede, Colo., Bachelor mine, 1,300-foot level.
16. Creede, Colo., Solomon mine, 1,500-foot level.
17. Idaho Springs, Colo., Stanley mine.
18. Tonopah, Nev., Mizpah mine; water from a bore hole 2,316 feet deep.

A study of these data shows clearly that the salts most abundant in mine waters are the sulphates, and further, that there is usually present an excess of acid radicles over basic; i.e., the solutions are acid in most cases. The preceding analyses are all of waters taken at some depth, hence must be assumed to be much more nearly neutral than the waters near the surface, since the tendency of descending waters is to become less acid through reaction with minerals. At Creede, as will be noted, the waters at the 1,500-foot level have actually become alkaline through the solution of carbonate in excess. It is a significant fact that this level is below the zone of secondary enrichment.[1]

The amount of ferric and ferrous salts present in the waters, as shown by the analyses, is surprisingly small. This is probably to be explained by the fact that iron salts are very easily precipitated by carbonates, which are here present in large amount. On the whole, the analyses tend to confirm the hypothesis that the active agents in the secondary processes are acid sulphate waters. They would also suggest that carbonate solutions may be a factor

[1] W. H. Emmons, unpublished manuscript.

in the processes, but this supposition should be confirmed by analyses of waters from horizons somewhat nearer the surface than those from which the above samples were taken.

EXPERIMENTAL WORK

The experimental work described in this paper deals with the following questions:

a) Solvent effect of sulphuric acid and ferric sulphate on argentite and its associated sulphides; both natural and chemically pure artificial minerals being used.

b) The solvent effect exerted on metallic silver by the various reagents that may occur in ground-waters, such as sulphates, chlorides, nascent chlorine, sulphuric and hydrochloric acids.

c) Solvent effect of ferric sulphate solutions on silver chloride.

d) Effect of the presence of ferric sulphate on the solubility of silver sulphate.

e) The equilibrium in dilute solutions between ferric, ferrous, and silver sulphates and native silver.

f) The substitution of silver for antimony or arsenic in the previously formed sulphides of these elements.

g) The reaction of metallic silver with precipitated sulphur.

As these experiments deal with somewhat widely different subjects, each series will be described and discussed separately. All of them were made under conditions approximating those which obtain in ground-waters. The temperatures were uniformly room temperatures, about 22° C. Pressures were atmospheric pressures. Concentrations of solutions were small, usually decinormal; these, although somewhat greater than those that obtain in ground-waters, may be confidently assumed to cause differences only in the speed, and not in the nature, of the reactions which take place.

The paper also includes a discussion, based on the experimental work of Barlow[1] and Schierholz,[2] of the effect of chloride solutions on the solubility of silver chloride, and the precipitation of the silver from such solutions as sulphide.

[1] Barlow, *Jour. Am. Chem. Soc.*, XXVIII (1906), 1446.

[2] Schierholz, *Sitzungsberichte der Kaiserlichen Akademie der Wissenschaften zu Wien*, 101, 2*b* (1890), 8.

METHOD OF PROCEDURE

The mineral to be tested was first powdered. In the preliminary experiments natural minerals were used, and only that portion which would pass through a 40-mesh sieve was used. It was thought, however, that the unequal sizing of the mass of mineral so obtained might affect the results materially. Therefore in the later experiments with chemically pure materials, only the fraction that passed an 80-mesh and was held by a 100-mesh sieve was used. Of this material a certain amount, usually 1.0000 gm., was weighed out, washed into a flask, and covered with 200 c.c. of the solution whose action was to be tested. The corked flask was then set away in the dark room at room temperature. After standing for a period of from one to three months, during which time the flask was shaken almost daily, the contents were analyzed. In some cases the analysis was of the liquid contents, after the solid residue had been removed by filtration; in others, where such analysis would prove difficult, it was thought sufficient to determine the materials in solution qualitatively, and the loss of weight of the solid residue. The latter was done by filtering into a weighed Gooch crucible, drying at 120° C., and weighing. This procedure was always adopted when the minerals used were the double sulphides pyrargyrite and polybasite.

Where stibnite was the sulphide acted upon, the procedure differed, in that the solutions themselves were analyzed. This was done because of the ease of the analysis and for the greater accuracy thereby obtainable. In the absence of ferric sulphate the solutions were repeatedly evaporated to dryness in the presence of nitric acid. The resulting precipitate was then heated to a dull-red heat, whereby it was converted into the oxide Sb_2O_4, then cooled, and weighed. Where ferric sulphate was present, hydrogen sulphide was passed in until there was no further precipitate. The solution was then filtered, the filtrate being repeatedly passed through the filter until clear, after which the precipitate was dried and washed with carbon disulphide to remove excess of sulphur. The antimony trisulphide remaining on the filter was redissolved in concentrated hydrochloric acid, the resulting solution mixed with concentrated nitric acid, and cautiously evaporated on a water

bath. As fast as the solution became colorless, more nitric acid was added, until further addition caused no change of color. The solution was then evaporated to dryness, the precipitate heated to a red heat, cooled, and weighed. Trial of this method with a weighed amount of pure antimony trisulphide showed it accurate to 1 per cent.

MAKING UP SOLUTIONS

A ferric sulphate solution was made, containing 35 grams of Kalhbaum's C.P. powdered ferric sulphate per liter. This gave a solution nearly F/20 (actually 0.0535 F. An F/1 solution=solution containing 1 formula weight in grams per liter). The sulphuric acid solution used was roughly F/20. That used in the first series of experiments was 0.0635 F; that used in the second series, 0.0502 F. These solutions will hereafter be mentioned simply as "ferric sulphate solution" and "decinormal sulphuric acid," and in the tables will be designated as "F" and "A," for brevity. A proportionality, such as A:F::1:3, indicates the proportions of acid and ferric solutions. The total volume of all solutions, unless otherwise stated, is 200 c.c.

ACTION OF SOLUTIONS ON MINERALS. SERIES 1

As may be seen from the tables, this series of tests included not only the silver minerals, but also those with which it is most closely associated, i.e., the sulphides of arsenic, antimony, and lead. Copper sulphide was not tested, since Vogt[1] had already proved its ready solubility in ferric solutions. The table also shows that both the dilute sulphuric acid and the dilute ferric sulphate solutions exert a powerful solvent action on all the minerals tested except argentite; that in each case the action is much more powerful when ferric sulphate is present; and that, except in the case of galena, an increase in the concentration of the ferric sulphate does not cause a corresponding increase in the solvent action. The absence of results in the case of the lump argentite is rather to be ascribed to the smallness of the surface exposed than to an actual absence of action. This will be shown in the table (Series 2).

[1] Vogt, *Genesis of Ore Deposits* (1896), p. 676, footnote.

SERIES I

Solution	Mineral	Loss of Weight	Time	Remarks
H_2SO_4......	Pyrargyrite 1.000 gm.	0.0130 gm.	81 days	Solution contained Sb, Ag
Acid: Fer. Sulph.=3:1 .	Pyrargyrite 1.000 gm.	.0290	81	Solution contained Sb, Ag
A:F::1:1...	Pyrargyrite 1.000 gm.	0.0272	81	Solution contained Sb, Ag
A:F::1:3..	Pyrargyrite 1.000 gm.	0.0268	81	Solution contained Sb, Ag
A..........	Polybasite	.0075	81	Solution contained Sb, Ag
A:F::1:1...	Polybasite	.0212	81	Solution contained Sb, Ag
A..........	Argentite, lump	.0000	83	
A:F::3:1...	Argentite, lump	.0000	83	
A:F::1:1...	Argentite, lump	.0002	83	
A:F::1:3...	Argentite, lump	.0022	83	
Water......	Argentite, lump	.0010	83	
A..........	Orpiment	0.0108	81	Solution contained As
A:F::1:1...	Orpiment	.0780	81	Solution contained As
Water......	Stibnite	....	102	Some sol. lost. Test gave a little Sb and SO_4
A..........	Stibnite	....	102	Solution analyzed, yielded .0185 gm. Sb_2O_4
A:F::1:1...	Stibnite	....	102	Solution analyzed, yielded .0255 gm. Sb_2O_4 solutions of 500 c.c. in each case
A..........	Galena 1.000 gm.	.0714 gm. gain of weight	81	Residues gained in weight due to formation of $PbSO_4$. 75 c.c. of solution used in each case
A:F::2:2...	Galena	.0924 gm. gain	81	
A:F::1:2...	Galena	.1700 gm. gain	81	

The fact that the solubility of the sulphides is so much greater in the presence of ferric sulphate, but is not at all proportional to the concentration of the latter salt, is probably to be explained by the hypothesis that the active agent is really the sulphuric acid, while the ferric sulphate exerts little direct action. The reaction of sulphuric acid on a sulphide may be represented by the equation $Ag_2S+H_2SO_4=Ag_2SO_4+H_2S$. This reaction, like most others, comes to an equilibrium. It must stop as soon as the product of the concentrations of the silver ion and the sulphide ion in the solution becomes equal to the solubility product of the sulphide acted upon (in this case Ag_2S). As the solubility products of most of the insoluble sulphides are very small,[1] the reaction in these cases can proceed but for an almost immeasurably short distance before stopping. But if some substance present remove the hydrogen sulphide as fast as formed, the reaction may proceed till all the ferric sulphate is used up. This is probably the main function of the ferric sulphate, which reacts thus with hydrogen sulphide: $Fe_2(SO_4)_3+H_2S=2FeSO_4+H_2SO_4+S$. If this be the true explanation of the action of the ferric sulphate, then it is to be expected that a small amount of ferric sulphate would cause as powerful a solvent action as a larger amount. The increased action in solutions more concentrated in ferric sulphate, shown especially in the case of the galena, may be ascribed either to a direct oxidizing effect of the sulphate on the sulphide or to the increased speed with which the more concentrated sulphate solution destroys the hydrogen sulphide formed.

If this explanation of the function of the ferric solution be the true one, two questions naturally arise: (*a*) Why is a measurable loss obtained experimentally when pure sulphuric acid acts on the sulphides? and (*b*) Was the reaction really at an end when the measurements taken in the experiments were made? In answer to question (*a*) the writer suggests that the oxygen of the air acts like the ferric sulphate, in removing hydrogen sulphide from solution, thus: $H_2S+O=H_2O+S$; its action is much slower than that of the ferric sulphate, however, so that the action of the acid on the

[1] Knox, *Trans. Faraday Soc.*, IV (1908), Part I, p. 29. Knox determined the solubility product of Ag_2S as 3.9×10^{-50}; of CuS as 1.2×10^{-42}; of PbS as 2.6×10^{-15}.

sulphide is less. In answer to question (*b*), we must conclude in the light of the hypothesis given that the action of the acid on the sulphide was not at an end, nor would it end till the ferric salt or the sulphide was used up. This might be tested by a series of experiments similar to the above, and lasting for a year or more; but time did not permit such test.

ACTION OF SOLUTIONS ON MINERALS. SERIES 2

To make certain that the losses in weight obtained in the last table were not due to the presence of soluble impurities in the natural sulphides, some of the above experiments were repeated with chemically pure substances. For the pyrargyrite used the writer is indebted to Mr. Sayrs A. Garlick, of the department of chemistry, who prepared it according to Sommerlad's method.[1] The other substances were prepared by the writer. The results are given in the following table.

SERIES 2

Solution	Mineral	Loss of Weight	Time	Remarks
Water.........	Argentite	0.0010 gm.	98 days	
A............	Argentite	.0019	98	
A:F::3:1......	Argentite	.0062	98	
A:F::1:3......	Argentite	.0074	98	
Water.........	Pyrargyrite	.0111	101	
A............	Pyrargyrite	.0093	101	
A:F::3:1......	Pyrargyrite	.0120	101	
A:F::1:1......	Pyrargyrite	.0125	101	
A:F::1:3......	Pyrargyrite	.0144	101	
Water.........	Stibnite	.0175	84	Weights give weight of Sb_2O_4 obtained from analysis of solutions
A............	Stibnite	.0205	84	
A:F::3:1......	Stibnite	.0185	84	
A:F::1:3......	Stibnite	.0160	84	
F............	Silver chloride	......	33	Solutions gave no Ag
$F:H_2O::1:1$....	Silver chloride	.0000	33	
$N/5\ H_2SO_4$.....	Silver chloride	.0000	33	

It will be seen therefore that the reactions noted in Series 1 and 2 are of the same class. The values obtained in Series 2 are perhaps somewhat smaller than those in Series 1, but this may have

[1] H. Sommerlad, *Zeit. anorg. Chemie*, XV (1897), 173.

been due to the presence of a soluble impurity in the natural minerals; or perhaps the artificial materials may actually dissolve less readily than the natural. The results obtained from Series 1 are, however, fairly well substantiated, and the additional conclusion might be drawn that, in the case of the double compounds of silver with antimony or arsenic, it is the silver which is the less soluble constituent. This result is inferred from observation of pyrargyrite during the reaction; it turned black within a very few days, an effect which could be due only to accumulation of silver sulphide on its surface as antimony was leached out. The writer did not confirm this conclusion by analysis, however.

EFFECT OF NATURAL REAGENTS ON METALLIC SILVER

In the investigation of the effects that the substances in solution in natural waters might have upon metallic silver, the reagents used were sodium chloride solution, hydrochloric acid solution acidified with sulphuric acid, in the presence of manganese dioxide so as to insure the presence of nascent chlorine, sulphuric acid solution, and ferric sulphate solution. The silver used was chemically pure leaf silver, cut into pieces about 2 sq. cm. in area, freed from all tarnish by scraping with a dull knife, and weighed to 0.00001 gm. on an assay balance. These were placed in large test tubes, covered with 75 c.c. of solution in each case, tightly corked, and placed in the dark for 73 days at room temperature (22° C.). At the close of the time mentioned they were taken out, carefully washed and dried, and weighed. In the cases where the silver had been covered with a coating of chloride, this was removed before weighing by washing with ammonia.

Solution	Loss of Weight of Silver
N/10 NaCl	0.00000 gm.
N/10 NaCl:N/10 H_2SO_4::1:1+MnO_2	.01538
N/10 HCl	.04502
N/10 H_2SO_4	.00019
A:F::1:1	.08252

These experiments show clearly the powerful solvent effect exerted by ferric solutions on native silver. It is probably this reagent which leaches the silver from the outer zones of gold

nuggets.[1] The conclusion might also be drawn that the formation of native silver would take place to but a limited extent in the gossans of deposits containing much pyrite.

The solvent action of the acids in the above table is ascribed to the presence of air, which sets up an oxidation potential between the silver and the solution, and thus aids the solution of the silver. Acids cannot attack silver directly in the absence of air, since the solution tension of the silver is less than that of the hydrogen which would thereby be given off. This fact may account in part for the stability of native silver precipitated below the zone of oxidation.

ACTION OF FERRIC SULPHATE ON SILVER SULPHATE

During the course of the above experiments, in some cases unusually high concentrations of silver were noted in the solutions. The solubility of silver sulphate in pure water at room temperature, 22° C., determined by measuring the strength of a solution that had been standing with frequent shaking for some months in contact with solid silver sulphate in the dark, was 6.90 gm. per liter or 0.0211 F. Euler[2] gives a figure somewhat higher than this, 7.70 gm. per liter at 17° C. Wright and Thompson[3] give 7.28 per liter at 18° C. The addition of an ionized sulphate, such as ferric sulphate, would be expected to decrease the solubility of the silver sulphate; since in a saturated solution the ion product $[Ag]^2 \times [SO_4]$ must be a constant. This is not the case here, however. Experiments carried out by leaving solid silver sulphate in contact with ferric sulphate solutions of varying strengths for a month or more in the dark show that the concentration of the silver is actually very considerably higher in the ferric solutions than in the aqueous. The following table (p. 16) shows the results obtained.

It will be noted that even in the most dilute of these solutions the solubility of the silver sulphate is increased by about 10 per cent. The results in the higher concentrations, while interesting from a scientific point of view, are of no significance as regards secondary

[1] J. M. McLaren, *Gold* (1908), p. 22.

[2] Euler, *Zeit. physik. Chem.*, XLIX (1904), 314.

[3] *Phil. Mag.* (5), XVII (1884), 288.

Strength of Ferric Solution	Concentration of Silver in Solution
0.0000 formula wt. per liter	0.0211 formula wt. Ag_2SO_4 per liter
0.0067	.02324
.0134	.02404
.0267	.02404
.0401	.02476
.0535	.02470
.062	.02508
.124	.02657
.248	.03012
.372	.02908
.496	.02864
.620	.03123

enrichment, as the concentration of ferric salt in earth waters probably never exceeds 0.05 F.

The cause of this behavior may be as follows: silver sulphate ionizes primarily into the ions Ag and $AgSO_4$, secondarily into the ions 2Ag and SO_4. The concentration of the silver *ions* is absolutely limited by the equation $\frac{[Ag]^2 \times [SO]_4}{Ag_2So_4} = \text{a constant}$. The addition of a large concentration of sulphate ions, as by the addition of ferric sulphate, must correspondingly decrease the concentration of the silver *ion* present. Since, however, the concentration of the silver in the solution increases, much of the silver must be present in some non-ionized form. The recent work of Harkins[1] would make it seem probable that the silver is present as part of the complex ion $AgSO_4$, the solubility of which would of course not be affected by the presence of the SO_4 ion.

EQUILIBRIUM BETWEEN FERRIC, FERROUS, AND SILVER SULPHATES

The reaction $Fe_2(SO_4)_3 + 2Ag = 2FeSO_4 + Ag_2SO_4$ has already been studied by Stokes,[2] and the fact noted that it is an equilibrium reaction, which proceeds to the right with rising temperature. In ore deposits where secondary enrichment is going on, the ferric sulphate formed in the upper parts of the oxidized zone must be

[1] Harkins, *Jour. Am. Chem. Soc.*, XXXIII (1911), 1836.

[2] Stokes, *loc. cit.*

gradually changed to the ferrous state as the solutions descend, by reaction with hydrogen sulphide sulphides and other reducing agents. A descending solution containing ferric, ferrous, and silver sulphates may thus react with the sulphides with which it comes in contact, perhaps taking more silver into solution, until the concentration of the ferrous salt present reaches a definite relation to that of the ferric and silver salts, expressible by the equation

$$\frac{C_{\mathrm{Fe}'''} \times C_{\mathrm{Ag}}}{C_{\mathrm{Fe}''} \times C_{\mathrm{Ag}'}} = K$$

where

$C_{\mathrm{Fe}'''}$ . . . . = concentration of ferric ion in solution
$C_{\mathrm{Fe}''}$ . . . . = concentration of ferrous ion in solution
$C_{\mathrm{Ag}'}$ . . . . = concentration of silver ion in solution
C_{Ag} . . . . = concentration of metallic silver in solution
K = a constant

Since C_{Ag} is extremely small and a constant, we may divide both members of the equation by it, and obtain

$$\frac{C_{\mathrm{Fe}'''}}{C_{\mathrm{Fe}''} \times C_{\mathrm{Ag}'}} = \frac{K}{C_{\mathrm{Ag}}} = K_2, \text{ a constant.}$$

It is evident that, given this constant, and an analysis of the earth waters containing the salts mentioned, at various depths, the horizon at which solution would cease and precipitation would begin can be determined. It becomes, therefore, a matter of importance to determine the value of the constant. To accomplish this, a ferrous sulphate solution was made of about F/20 in strength, by dissolving chemically pure ferrous sulphate in N/50 sulphuric acid solution. The ferrous content of this solution was then determined by standard potassium permanganate, the total iron by reduction with test lead and titration with permanganate, and the total sulphate by precipitation as barium sulphate. To 100-c.c. portions of this solution were then added quantities of a saturated silver sulphate solution varying from 10 c.c. to 100 c.c.; the flasks were immediately corked, the whole securely sealed with melted paraffin to prevent access of air, and set away to come to equilibrium. German standard pipettes were used throughout in measuring the solutions. Precipitation of silver, which came down as a cloud of silvery flakes, took place almost at once, and equilibrium was

probably reached in a few hours; but owing to delays the solutions remained for 65 days before they were analyzed. They were shaken at intervals during this time. In the analyses, the ferrous salt was first determined by standard permanganate; great care being taken to stop the titration as the first faint tinge of pink appeared. The silver was determined in the same sample by titration with ammonium thiocyanate.[1] The method was found very accurate, duplicates checking to one-tenth of 1 per cent. The ferric salt was determined by difference. In calculating the constant from the results obtained, it was assumed that the salts were all completely ionized in the dilute solutions used. This assumption is scarcely permissible; but the writer was unable to obtain any figures on the ionization of ferric sulphate in solutions of different strengths and for the other salts the difference between complete ionization and their ionization in these solutions is small. Concentrations in the following table are all given in formula weights per liter.

$Fe_2(SO_4)_3$	$FeSO_4$	Ag_2SO_4	K_2
0.00370	0.03972	0.000439	212.1
.00475	.03370	.000703	200.4
.00556	.02876	.000952	203.2
.00626	.02451	.001298	196.7
.00677	.02101	.001708	188.8
.00695	.01849	.002294	163.5
.00718	.01614	.002738	162.5
.00737	.01406	.003226	162.5
.00748	.01231	.003715	163.7
.00749	.01094	.004200	163.0

From the results of the last five analyses the constant would be 163. The higher results of the first five analyses are ascribed to increasing hydrolysis of the ferric salt as its dilution increases. This would make the amount of the ferric *ion* in solution less than the total ferric value. It is the latter which is measured, while only the ionized portion enters into the equilibrium. Therefore, since in the fraction $\frac{C_{Fe'''}}{C_{Fe''} \times C_{Ag'}}$ the numerator is too large, the value of the fraction must likewise be too large. If this is the true

[1] Volhard, *Liebig's Ann. d. Chem.*, CXC, 1.

cause of the increase of K_2, an increase of the acidity of the solution by addition of sulphuric acid should bring K_2 back to its true value, by decreasing the hydrolysis of the ferric sulphate. This, however, has not yet been experimentally verified.

This constant is given with some hesitation; it should be verified by further experimental work before final acceptance. Moreover, as it stands it expresses a relation merely between the concentrations of the various salts involved, not between the concentrations of their ions; but in the absence of accurate determinations of the extent of ionization of these salts, this is unavoidable.

REACTION OF SILVER CHLORIDE WITH SODIUM CHLORIDE

The question of the secondary enrichment of silver deposits through the agency of chloride solutions has long been discussed. Silver chloride has a solubility in water of 0.0016 gm. per liter at 20° C.[1] It has often been stated that the presence of sodium chloride in the water increases the solubility. The information already at hand in regard to this question is comprised in the following table:

NaCl in Solution	AgCl in Solution	Temperature
gm. per liter	gm. per liter	
34.3	0.0018	20° C.**
46.0	.0025	20° C.
57.5	.0047	20° C.
76.7	.0125	20° C.
115.0	.031	20 °C.
153.0	.090	20° C.
230.0	.313	20° C.
100.0	.025	15° C.†
142.9	.071	15° C.
181.8	.182	15° C.
219.8	.439	15° C.
235.3	.706	15° C.
256.4	1.03	15° C.
263.1	1.27	15° C.

** Barlow, *Jour. Am. Chem. Soc.*, XXVIII (1906), 1446.
† Schierholtz, *Sitzungsberichte der Kaiserlichen Akademie der Wissenschaften zu Wien*, 101, 2b (1890), 8.

Thus it requires the presence in solution of 34.3 gm. of sodium chloride per liter, or 34,300 parts per million, to raise the solubility of the silver chloride to its value in pure water. In all sodium

[1] Kohlrausch, *Zeit. phys. Chem.*, L, 356.

chloride solution of less strength the solubility of the silver chloride must be less than its solubility in pure water; the solubility curve will consequently be as shown in Fig. 1, which was obtained as follows: silver in chloride solutions exists in two forms, as silver ion and as part of some non-ionized molecule or some complex ion. The concentration of the silver ion in solution is inversely proportional to that of the chloride ion according to the equation $C_{Ag} \times C_{Cl} = k$, a constant. Hence addition of sodium chloride to silver chloride solution will very rapidly reduce the concentration of silver ion to a very small quantity (see Fig. 1). Silver in the non-ionic form may be present as molecular silver chloride, but the amount of this is so small as to be negligible; it may also be present in combination with sodium chloride, forming compounds of composition as yet undetermined, but which may be supposed, from analogy with the corresponding cyanide compounds, to have the formulae $NaAgCl_2$ or Na_2AgCl_3. The silver would then enter into solution as part of the complex negative ion $AgCl_2'$ or $AgCl_3''$, whose solubility would not be affected by the presence of chloride ion. The table shows that the amount of AgCl in solution as complex ion attains 0.0018 gm. per liter only when the amount of sodium chloride present is 34.3 gm. per liter, and that thereafter the concentration of complex ion increases proportionally much faster than does the concentration of the soldium chloride; hence it is probable that in sodium chloride solutions of strength less than 34.3 gm. per liter the concentration of complex ion, and therefore that of silver, will never be more than proportional to the amount of sodium chloride present, but usually less. The curve showing the total silver in solution will consequently be of the form shown in Fig. 1.

From these experiments, therefore, it is concluded that only when the amount of sodium chloride in ground-waters exceeds 34.3 gm. per liter may such waters be solvents superior to those in which chlorides are absent. Such concentrations occur rarely in nature.

An accurate determination of the strength of the sodium chloride solution which contains the minimum amount of silver chloride will be of value as rendering possible the determination of the

causes of secondary cerargyrite enrichment in any deposit, because silver solutions containing less sodium chloride than this "mini-

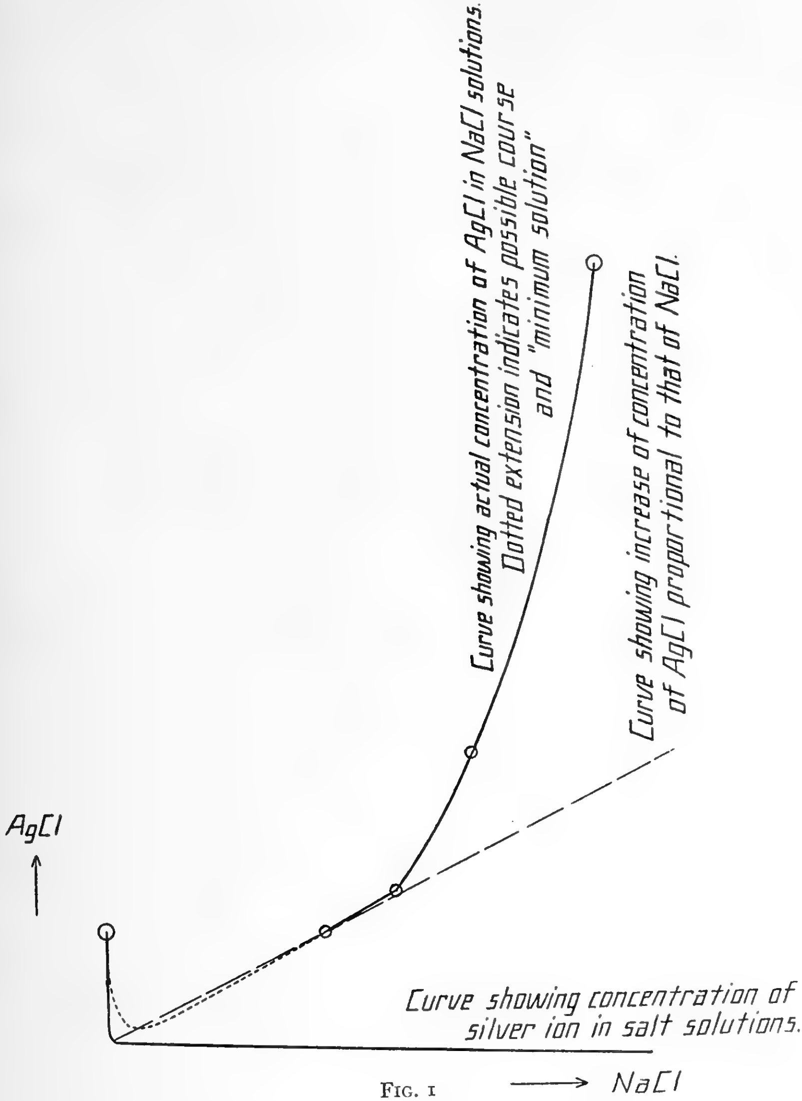

Fig. 1

mum solution" will precipitate silver chloride if the concentration of the sodium chloride increases; while, on the contrary, silver solu-

tions in which more sodium chloride is present than in the "minimum solution" will precipitate silver chloride *on dilution.*

Can the addition of sodium chloride to silver chloride solutions ever so reduce the amount of silver present that the precipitation of silver as sulphide becomes impossible?

This relation is determinable mathematically. The solubility of silver chloride in water at 20° C. is 0.0016 gm., or 1.1×10^{-5} mols per liter. Assuming complete dissociation, as is permissible at such dilutions for a salt of a strong acid and a strong base, we should have present in solution 1.1×10^{-5} mols of Ag ion, and the same number of mols of Cl ion. The solubility product for the salt is therefore $(1.1 \times 10^{-5})^2 = 1.24 \times 10^{-10}$.

The concentration of silver sulphide aqueous solution is 2.2×10^{-17} mols per liter,[1] and at such extreme dilution the salt may be assumed to be completely ionized. The amount of Ag ion present in a saturated solution is therefore 4.4×10^{-17} mols per liter, and the amount of sulphur ion, one-half of this.

The addition of sodium chloride to silver chloride solution, as before shown, decreases the amount of silver ion present in solution. To prevent the precipitation of the silver as sulphide, the amount of silver ion would have to be decreased till the product of the silver ion and the sulphur ion present in solution was equal to the solubility product for silver sulphide, i.e., 3.9×10^{-50}. If we assume the concentration of sulphur ion never greater than the amount given above, 2.2×10^{-17}, then the concentration of the silver ion must decrease to 4.4×10^{-17} if precipitation is not to occur. Substituting this value into the equation $C_{Ag} \times C_{Cl} = 1.24 \times 10^{-10}$, we obtain 2.8×10^{6} as the value of the Cl ion. Disregarding the infinitesimal amount of Cl ion in combination with Ag ion, we should therefore require to have present 2.8 million mols, or about 165 million grams, of ionized sodium chloride per liter, to prevent the formation of silver sulphide under the given conditions. With higher concentrations of sulphur ion, even more sodium chloride would be required to prevent the formation of silver sulphide. As such concentrations of sodium chloride are impossible, it is evident that the amount of this salt in meteoric waters can

[1] Knox, *loc. cit.*

never rise so high as to bar the precipitation of silver as sulphide from solutions in which it is carried as chloride.

MECHANISM OF THE SOLUTION OF SILVER MINERALS IN METEORIC WATERS

The work of Gottschalk and Buehler, coupled with that of the writer, renders possible a statement of the method by which the silver sulphides are taken into solution in the ground-water. The potentials of the minerals studied by Gottschalk and Buehler, measured against that of copper, include marcasite, +0.37 volt; argentite, +0.27 volt; pyrite, +0.18 volt. If we assume then an ore-body of argentite and pyrite, the pyrite, whose potential is lower than that of the argentite, will be oxidized, while the argentite is protected from *direct* oxidation. The silver can then be taken into solution only by the secondary action of the oxidation products of the pyrite, ferric sulphate, and sulphuric acid. But if the iron sulphide of the deposit be marcasite—a rare case—then we might expect a *direct* oxidation of the silver sulphide to sulphate by the electrolytic action set up since marcasite possesses a higher potential than argentite.

Moreover, the iron sulphides are *the only sulphides* which can effect the solution of the argentite. The potential of argentite is higher than that of the sulphide of any other metal except iron, hence it can undergo *direct* oxidation only in the presence of iron sulphide; and since no sulphides but those of iron produce by oxidation the solvents ferric sulphate and sulphuric acid, argentite can undergo *indirect* oxidation likewise only in the presence of iron sulphide. Therefore Weed's deduction, that the secondary enrichment of silver is dependent on the presence of pyrite in the lodes, appears to be confirmed.

FORMATION OF SILVER SULPHIDE

The formation of the complex silver minerals by simultaneous precipitation of the component sulphides was not attempted, on account of lack of facilities for handling large volumes of dilute solutions. It was thought, however, that these might be formed by substitution of silver for arsenic or antimony in the pre-existing

sulphides of these elements. To test this theory, well-crystallized specimens of realgar, orpiment, and stibnite were powdered, the stibnite to pass an 80-mesh, the others a 40-mesh screen. The stibnite was covered with a saturated (about N/30) silver sulphate solution, the realgar and orpiment with N/40 silver nitrate solutions, after which the mixtures were put away in the dark. The stibnite was analyzed after 36 days, the realgar and orpiment after 68 days, the analyses being conducted by passing a current of dry chlorine over the material heated to a low red heat. The silver remained in the tube as silver chloride, together with earthy impurities; the other substances volatilized as chlorides. After weighing, the silver chloride was dissolved with warm ammonia, and the weight of the impurities determined. Results were:

Stibnite contained 1.3 per cent Ag
Realgar contained 1.9 per cent Ag
Orpiment contained 9.8 per cent Ag

Since pyrargyrite contains 60 per cent and proustite 65 per cent of silver, the amounts of silver entering into the sulphides in these experiments were far below those necessary to give a true silver mineral. Moreover, the reaction in the case of the orpiment was visibly instantaneous, the powder changing from brilliant yellow to black at once. As the solutions used contained much more silver than ground-waters commonly do, it would appear improbable that true silver minerals are formed in this way.

The formation of argentite can easily be explained by the action of hydrogen sulphide or a metallic sulphide on silver-bearing solutions. As has been shown by R. C. Wells,[1] the action of dilute sulphuric acid on pyrrhotite, galena, sphalerite, and other natural sulphides produces hydrogen sulphide. This might be supposed to react with the silver solution and yield silver sulphide, and, as already mentioned, would do so in the case of chloride solutions carrying silver. But in the case of sulphate solutions a complication is introduced. Hydrogen sulphide would probably precipitate the silver as sulphide here also, but it tends in addition to attack the ferric sulphate present in the solutions, and to reduce it to the ferrous form with separation of sulphur. The formation of ferrous

[1] R. C. Wells, unpublished manuscript.

salt would precipitate silver from solution as metal, so that a mixture of sulphur and metallic silver might result. Sulphur in the ordinary form will not react with silver, except under very high pressures,[1] which cannot be assumed under the conditions existing. However, as has been recently shown,[2] precipitated sulphur is not crystalline, but amorphous, and might therefore be expected to possess a greater chemical activity than crystalline sulphur. To test this, an acid solution of ferric sulphate was partially reduced to ferrous salt by passing in hydrogen sulphide, after which it was allowed to stand for a few minutes in order that all the hydrogen sulphide in solution might be used up. Some silver previously precipitated by reaction of ferrous sulphate with silver sulphate was then added. Reaction did not occur at once, but at the end of twenty-four hours all of the silver had been altered from silvery white flakes to black silver sulphide. To make certain that the black mass did not consist of marcasite, as might be suspected from the work of Allen,[3] some sulphur was precipitated by treating sodium thiosulphate with sulphuric acid, filtered, washed, and added to some washed silver prepared as before. The results were the same, hence the end product of the reaction of hydrogen sulphide with silver solutions is silver sulphide, whether it is the first product of precipitation or not.

The conclusion may also be drawn from this reaction, that if in any deposit native silver were the first product precipitated, and at some subsequent time sulphur were also formed there, then the sulphur and silver would combine to form argentite, the completeness of the alteration depending on the amount of sulphur. Such a hypothesis might possibly account for the mixtures of secondary argentite and native silver found at depths in some deposits, notably at Creede, Colo.

SUMMARY

Secondary sulphide enrichment of a primary silver deposit is brought about by reactions of silver or its sulphides with the sulphides of iron and their products of oxidation.

[1] Spring, *loc. cit.*

[2] Brownlee, *Jour. Am. Chem. Soc.*, XXIX (1907), 1032.

[3] Allen, *loc. cit.*

When the iron sulphide present is pyrite, the silver sulphide is converted into sulphate wholly by the sulphuric acid and the ferric sulphate produced by the oxidation of the pyrite, according to the equation on p. 5.

When marcasite is present, as it rarely is in quantity, silver sulphide may be oxidized in part directly to silver sulphate by electrolytic action, and in part may be converted into sulphate by the action of the oxidation products of the marcasite.

Sulphuric acid and ferric sulphate exert a powerful solvent action both on silver sulphide and on its companion sulphides, such as galena, chalcocite, orpiment, and stibnite. Of these, silver sulphide is the least affected. In all cases the action is much more powerful when ferric sulphate is present than when sulphuric acid acts alone.

Except in the case of galena, the solvent action does not seem to be proportional to the concentration of the ferric sulphate present. This suggests that the sulphuric acid is really the active agent, and that the ferric sulphate acts principally as an agent for the removal from solution of hydrogen sulphide formed during the reaction.

A mixture of sulphuric acid and ferric sulphate has a powerful solvent action on metallic silver, hence, in an ore-body containing much pyrite, little native silver may be expected in the gossan; and conversely, if much native silver be found in the gossan, the ore-body cannot have contained much pyrite, and little secondary enrichment should be expected.

The presence of ferric sulphate in the ground-waters increases the solubility of silver sulphate in them. This is probably due to the formation of a complex ion $AgSO_4$ by the silver, when ferric sulphate is present in solution.

Equilibrium in silver-bearing solutions between ferric, ferrous, and silver sulphates is such that the reduction of ferric solutions to the ferrous condition by any means will rapidly precipitate the silver in the metallic form. Precipitation of silver will not cease till all the ferric salt is reduced to the ferrous state. Hence the vertical extent of the zone of precipitation and its proximity to the surface will depend on the rapidity with which this reduction goes on. If reduction be slow, native silver may thus be formed even

at considerable depths. Native silver so precipitated will be comparatively stable in the presence of earth waters. Acids will not attack it in the absence of oxygen, since the solution pressure of hydrogen is greater than that of silver. Ferric sulphate cannot attack it so long as the ground-waters contain enough silver sulphate to preserve equilibrium between the ferric and ferrous salts. Precipitated sulphur may convert it into sulphide.

The presence of sodium chloride in ground-water does not increase the solubility of silver chloride therein, unless the amount of sodium chloride rises above 34.3 gm. per liter; on the contrary, it decreases the solubility. The solubility-curve of silver chloride in sodium chloride solutions is shown in Fig. 1. Terming the sodium chloride solution which contains the least amount of silver chloride the "minimum solution," then solutions which contain less sodium chloride than this minimum solution will precipitate silver chloride on taking up more sodium chloride; solutions with more sodium chloride than the minimum solution will precipitate silver chloride on dilution.

Silver chloride solutions containing sodium chloride in any concentration may form secondary silver sulphide wherever they encounter hydrogen sulphide or any other substance that yields sulphur ion even in minute quantity.

Cerargyrite appears to be stable in presence of sulphuric acid and ferric sulphate.

The action of dilute silver solutions on realgar, orpiment, and stibnite results in the substitution into these minerals of some silver; but the amounts so substituted were found to be so small that it appears doubtful whether the complex sulpho-salts of silver can be formed in this way.

Precipitated sulphur combines with precipitated silver at ordinary temperature and pressure to form silver sulphide. Silver sulphide is also formed by the direct reaction of hydrogen sulphide with silver-bearing solutions.

CONCLUSION

The accuracy of the application of laboratory investigations to geologic problems must be verified by field observations; otherwise, however correct the experimental work, it cannot be claimed

to solve the problem attacked. The data at hand dealing with the secondary enrichment of silver are scarcely complete enough to make such verification of this work at the present time. The full solution of the problem would require (*a*) approximately accurate estimates of the proportions in which pyrite, primary silver sulphide, and secondary silver sulphides are present, in a large number of deposits; (*b*) more analyses of mine waters, and especially of waters from the same mine at different depths; (*c*) further observations on the changes in chemical and mineralogical composition of lodes with depth; (*d*) accurate analyses of the thin veinlets of secondary material that cut primary sulphide ores; (*e*) in cerargyrite deposits, analyses of the waters at top and bottom of the cerargyrite zone. Such data would at once render it possible to determine whether or not the processes of the secondary enrichment were subject to factors other than those mentioned in this paper.

In conclusion, the writer wishes to express his thanks to Professor W. H. Emmons, who suggested this research and generously placed at the writer's disposal his invaluable fund of practical information on the subject. He also wishes to make grateful acknowledgment to Professor Julius Stieglitz for much kind assistance and valuable criticism; and to Mr. A. D. Brokaw for many useful suggestions. As regards the work of this paper, the writer recognizes the incomplete and, as it were, qualitative nature of many of the results obtained; this, however, was unavoidable on account of the preliminary nature of the work, the large field covered, and the limited time at his disposal. It is his aim to investigate more accurately in the near future many of the problems as yet but incompletely solved.

THE GEOLOGY OF LUZON, P.I.

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CONTENTS

INTRODUCTION

Luzon is the largest island of the Philippine group and, if not now, promises soon to be the most important island off the eastern coast of Asia. Because of its great strategic importance and because it is the home of the only Christianized people of Malay origin, it is of more than passing interest. Geologically, it is worthy of constant study as it is a link in that great "Circle of Fire" which girds the Pacific. From it, doubtless, are to be wrested

[1] Published with the permission of the Director, Bureau of Science, Manila.

important secrets relating to such questions as the former configuration of Asia, climatic changes, and possibly something of the early history of man. As a mining field, evidence is already abundant that Luzon will before many years have a place in the very first rank.

Finally, Manila, the capital of Luzon, through her Bureau of Science, an institution not surpassed anywhere in the Orient, will be the point from which, possibly, all the geology of the Orient will be correlated.

The dominant feature about Luzon, as is the case with other portions of the Archipelago, is the enormous coast line and the mountainous character of much of its interior. The effects on the character and pursuits of the people have been great. Some of these will be alluded to farther on in this paper. Luzon's geographical position is also noteworthy. She is in a region of tremendous rainfall (45 inches in 24 hours, Baguio Observatory record, July, 1911) and in the track of the most frequent and violent typhoons. As she extends from 10° to 21° north latitude and has much high level country, which is at the same time fertile, she could be colonized by white men.

PHYSIOGRAPHY

THE COASTAL PLAINS

The coastal plains about the Island of Luzon, are, as a rule, very narrow, the maximum width being about 10 miles. The mountains are nearly everywhere close to the sea. The best development of coastal plains is to be found north from Lingayen Gulf, because the northern part of Luzon has been longest under water, and erosion has had time to work on the mountains, carrying detritus down to the sea. The composition of the northern coastal plain consists almost entirely of alluvial and Piedmont deposits. Another fair development of coastal plain is found on both sides of the Tayabas Peninsula and around Batangas Bay. The east coast of Luzon is conspicuously lacking in broad coastal plains. It is a fact that the east coast is sinking in part, while the west coast is known to be rising in part. As evidence of this, I am citing the raised beaches and terraces along the Ilocos Norte coast on the

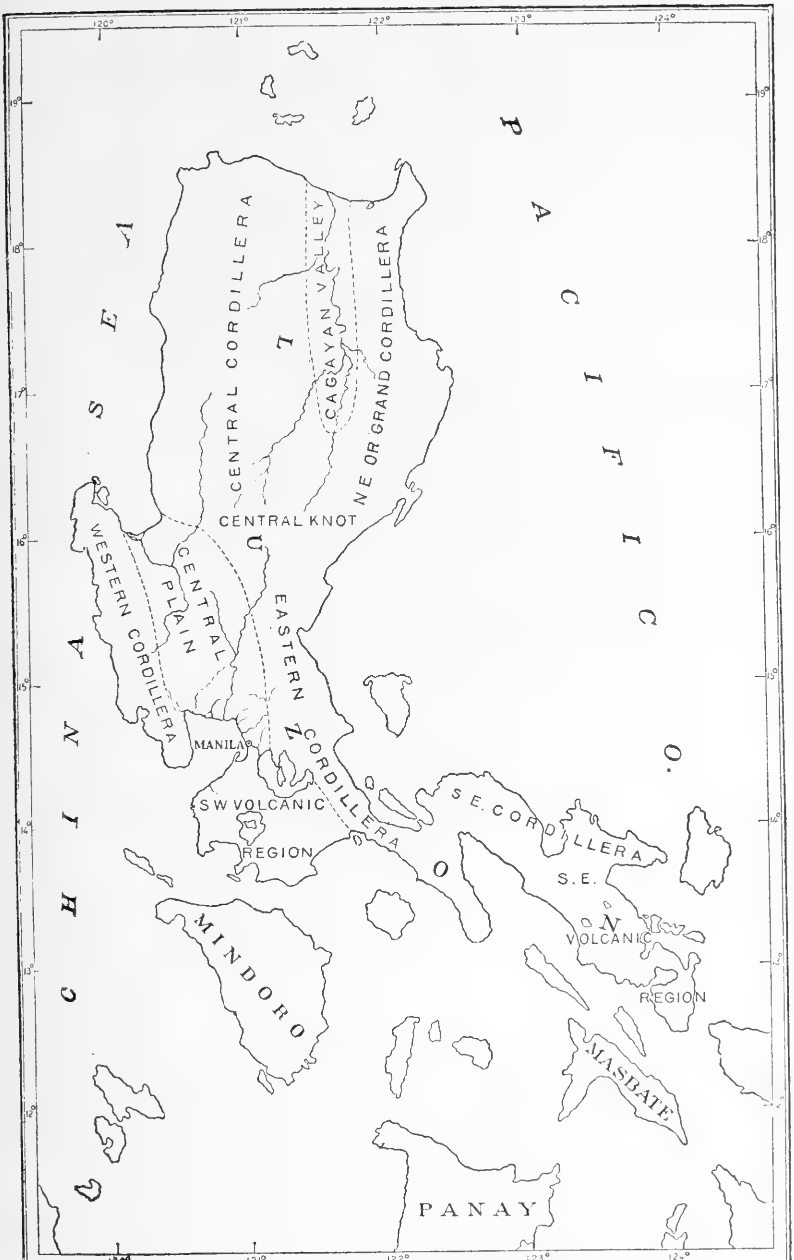

FIG. 1.—Map of Philippine Islands. (After Adams.)

west of Luzon, and the drowned river areas on the Camarines coast on the eastern side. We find extensive settlements on the western side of Luzon, on these coastal plains, the principal tribe being the Ilocanos, the members of which are perhaps the thriftiest and most energetic of all the tribes of the Philippines. These are the only people who produce all their own rice. On the eastern side of Luzon, the settlements are very, very scarce—in fact but little is known, or of the people north of Baler, except that they are not numerous.

THE CENTRAL PLAIN OF LUZON

The principal interior plain of Luzon is known as the Great Central Plain (Fig. 1) and is the chief place of settlement in the Philippine Islands. It is roughly, 120 miles long by 70 wide, stretching from Manila Bay on the south to Lingayen Gulf on the north. On the west, it is bounded by the Zambales Mountains, and on the east, by the Eastern Cordillera. This plain was probably the site of an ancient arm of the sea—a fact that has been called attention to by a number of geologists, among them Adams[1] who has drawn a hypothetical map of the Tertiary geography of the central portion of Luzon.

Composition.—In the northern and western portions this plain is largely composed of alluvial material, as shown by well-sections at Lingayen. In the southeastern part it is largely made up of pyroclastics, as can be seen in railroad and river cuts and numerous well-sections. That this pyroclastic material extended to a considerable depth is shown by the following well-section at Pasay near Manila:

SECTION OF WELL AT PASAY, RIZAL PROV., LUZON, P.I.

0	to	18	ft.	soil, sand, and seashells
18	"	83	"	gray and yellow silt with pebbles, shells, and calcareous concretions
83	"	87	"	fine to coarse basaltic pebbles and tuff
87	"	113	"	yellow-gray sand, some clay, fragments of soft tuff
113	"	160	"	yellow-gray tuff
160	"	180	"	yellow sand and tuff, small basaltic pebbles

[1] G. I. Adams, "Geological Reconnaissance of Southwestern Luzon," *Phil. Jour. Sci.*, V, No. 2.

180	to	463	ft.	light, yellow-gray tuff, partially with basaltic pebbles
463	"	483	"	fine dark sand, some clear grains, tuff, basaltic pebbles
483	"	546	"	fine grained tuff, light gray
546	"	570	"	dark sand, some clear grains
570	"	594	"	tuff, with small basaltic pebbles
594	"	634	"	yellow clay with small basaltic pebbles
634	"	690	"	dark sand
690	"	713	"	fine gray tuff
713	"	743	"	basaltic pebbles and fragments of tuff

Physiographic features.—At first glance, the most striking physiographic features of this plain are: (1) the drainage system; in the north the rivers flow to the north and in the south to the south; this is accounted for by warping; (2) the single extinct volcanic cone of Arayat, standing isolated in the center of this great flat; (3) the two large swamps and one lake located in the eastern part; (4) and the vast delta region of the Pampanga River which bounds Manila Bay on the north.

Farther along in this paper, I shall draw some conclusions regarding the human response to the physiographic and geologic conditions, showing how these features have controlled the human settlements, the intermingling of various tribes, and such like questions.

THE ALBAY PLAIN

We shall pass now to the second great interior plain, which is known as the Albay Plain (Southeastern Luzon). This plain is about as long as the one we have been considering, but is much narrower. It extends from Legaspi to San Miguel Bay. It is an old coastal plain, on the outer margin of which a volcanic cluster has been built up since this plain rose from the sea. The main drainage of this plain is to the north by way of the Bicol River. There are two or three small lakes which are little more than swamp-areas along the course of this river. To the west of this plain, the rocks are sedimentary, while to the east, as I have already said, they are recent extrusives. The material of this plain is largely made up of volcanic ash, bowlders, bombs, lapilli, and tuff. This region is the principal hemp region of the Philippine Islands, and I believe that the peculiar composition of this volcanic soil is largely responsible for this.

THE INTERMEDIATE UPLANDS

All of the territory which is not coastal plain or central plain, and which is not above 5,000 feet in elevation, I shall designate as the Intermediate Uplands. Most of the highlands of Luzon will come in this category. Topographically it consists of the foothills and the sloping flanks of the high Cordilleras. The rocks may be of all classes, but the chief formations are the folded Tertiary sediments, limestones, sandstones, and shales, with the coal-measures, which slope away from the central ranges. Also the lower, and generally worn-down, volcanic stocks will be comprised under this heading.

The population in the Intermediate Uplands consists largely of the less progressive types and of more or less recent white settlers, prospectors, etc. In certain parts of Luzon, such as in Batangas and Laguna Provinces, where the underlying formation is a decomposing volcanic material and where the country is not too greatly dissected by streams, there is a fairly prosperous population, but in the uplands of northern Luzon very little advancement can be noted. There are scarcely any roads and there is very little communication between the different communities. The greater dissection of the country by the streams has decreased the area of agricultural land, and unless the mineral resources be developed, the country will always remain comparatively backward. The people who inhabit those sections give very little promise of ever being able to take advantage of the mineral resources as these are usually low grade and refractory.

THE CORDILLERAS

The eastern Cordillera.—The eastern Cordillera has a general north-and-south trend, but is marked by great sinuosities, following pretty closely the east coast of Luzon, so that in its southern extension where it cuts through Ambos Camarines, particularly in the Caramoan Peninsula, it is running almost east and west. Very little is known about the eastern Cordillera and but few prospectors have crossed it. Here and there in the northern part, some adventurous ones, notably Messrs. Heise and Dudley, crossed. Ickis (formerly a mining engineer in this Bureau) made a recon-

naissance from Laguna de Bay to Infanta, and Pratt and Adams have been on the Caramoan Peninsula. A few boats have skirted the east coast of Luzon, but very fragmentary observations have been brought back.

It is needless to say that we know very little about the elevation of this Cordillera, except that it is much lower than the central Cordillera, and in several places, to which I shall refer later, the range is quite low.

We know practically nothing about the formations in the northern part of this range. Ferguson found a volcanic peak, Mount Kawa, near the northernmost point. Ickis has made a cross-section from Tanay to Infanta (Fig. 5), showing closely folded sediments, diorite, and andesites. Adams and Pratt found considerable andesite in the central part of the range in Ambos Camarines.

If we examine the map showing the distribution of civilized and wild peoples, published in the second volume of the first Philippine Census, 1903, we note that the whole eastern Cordillera from Cape Engano to Casiguran Bay, and, except for two or three spots as far down as Infanta, is inhabited by Negritos. Then, continuing along the coast almost to San Miguel Bay, there is a long strip pretty well taken up by Tagalogs. Then, in the Caramoan Peninsula, the Negritos are found again with some Bicols. At any rate the population is very scanty.

Beginning at the north, we find several well-defined passes through this range, and these passes are the location of trails leading from the interior to the coast. The first one runs from the headwaters of the Ilagan River eastward to Palanan Bay. Then about 50 miles south is another one leading across from the headwaters of the Cagayan River to Casiguran Bay. Only a few miles south of that is another which runs across from Cabanatuan to Baler. The next important pass is following the Chico River from Penaranda to Dingalen Bay. Farther south is the route followed by Ickis from Tanay on Laguna de Bay to Infanta. Another one extends from Pagsanjan to Mauban. Then from Lucena to Atimonan. In Ambos Camarines, this Cordillera splits up into two: one following as already described, the Caramoan Peninsula; the other stretch-

ing in a southeasterly direction down into Sorsogon, and this is crossed in two very important places—the first trail leads from Nueva Caceres to Pasacao, and the second from Albay to Pilar. These passes have been most important in the settlement of certain parts of the east coast. There has always been very little trading along the east coast and, by examining the map alluded to before, there are seen to be several isolated spots occupied by Tagalogs and it is my opinion that these Tagalogs have come across the mountains rather than by the longer way of the sea. From what we know of the history of the United States, mountains are great control-factors in the distribution of people. I have but to call attention to the Cumberland Gap leading from the Appalachian valleys into the "blue grass" regions of Kentucky and Tennessee. For a certain period in the history of the United States, practically the entire flow of the population was through this pass.

The central Cordillera.—The central Cordillera begins about the latitude of Lingayen Gulf and extends north to the northernmost point of Luzon. It is not a single range but consists of two or three parallel ranges. The eastern Cordillera and the central Cordillera start from what Adams calls the "central knot" which is the Caraballo Sur in northern Nueva Ecija. The principal range of this central Cordillera is the Polis Range about 25 miles east of Cervantes. In this range is Mount Polis or Amuyao, which is probably the highest peak in Luzon; Mount Data, which is 7,366 feet high, is another high peak in this Cordillera, and Mount Pulog east of the Agno River is also one of the highest points in the Philippine Islands (Fig. 2). On a recent trip into the northern country, I made a boiling-point observation on a peak 45 miles north of Baguio and found the elevation to be 8,236 feet, and there were a half-dozen peaks around me which were much higher. This Cordillera extends, as I have said, to the north coast, and keeps its high elevation practically throughout the whole extent. It is a region of great rainfall and steep slopes—much greater slopes than the material will stand on, so that landslides are of exceedingly frequent occurrence. The vegetation is very scanty, and practically the only forest tree is the pine (*P. insularis*).

The formations are largely igneous, diorite in the bottom of the

Fig. 2.—Topography in Cordillera Central of Luzon

canyon, and andesites on the upper slopes. There are no active volcanoes in this region but there are several extinct craters, and great areas of volcanic tuff. Around Baguio, the summer capital, there is a great deal of this material.

The population of this Cordillera is almost entirely made up of Igorots with the closely related tribes: Apayaos, Ifugaos, Ilongots, who are very scattered, and comparatively backward people, except in their knowledge of agriculture and irrigation. The Igorots of Lapanto practice the art of copper smelting (which was probably taught them by the Chinese) and with considerable success. The country is almost entirely without roads, but there are a great many Igorot trails which do not take any advantage whatever of the topography. The government, however, is building a horse trail which practically follows the backbone of the Cordillera for many hundred kilometers. It is proposed, in time, to make an automobile road out of this. Such a road will be of great benefit to the country and, already, there is a better feeling between these northern tribes and between them and the Philippine government.

As I said before, the Igorots take very little advantage of the topography; however there are several well-defined routes of travel; the principal one being the trail from Bontoc to Tuguegarao, from San Fernando to Baguio by the Naguilian trail and from Candon to Cervantes by way of Tiela Pass. From Tagudin to Cervantes and from Vigan across to Solano by way of the Abra and Chico rivers and then from Laoag across to the Abulog River by the Worcester trail. There is considerable travel by way of these routes, the passes being taken advantage of by the Ilocanos to go up into the Igorot country to trade. The Igorots, however, do not go down to the coast very much, and when they do, go usually for plunder or to buy dogs, which is one of their principal articles of diet. I do not know to what extent the Igorots use these passes. From my own knowledge of them it seems to make very little difference to them whether the road follows an easy grade or goes up and down hill; in fact they often take an up-and-down hill trail in preference to one on the level.

The western Cordillera.—The western Cordillera is generally known as the Zambales Range, extending from Olongapo north into Pangasinan Province. Another part of this range consists of a cluster of volcanic stocks in the Province of Bataan. This range of mountains is not by any means a continuous one—there being a few isolated high peaks—but in the main the range is not very elevated. The highest point in this range is Mount Pinatubo. This has never been accurately measured, but is in the neighborhood of 6,000 feet. Very little geological work has been done in this Cordillera. Von Drasche has done some work in the neighborhood of Iba, and Fanning has touched it in a few points in the neighborhood of Agno and Alaminos in Pangasinan, and I have been on the second highest peak of Pinatubo, about 5,500 feet; and also on one of the high peaks of Mount Mariveles, which is also about 5,000 feet high.

In general, the rocks of this range are volcanic extrusives, andesites, with marls and shales on the flanks. The Cinco Picos Range, however, on the western side of Subig Bay, consists of a totally different rock from that found on the east side, being a dense pyroxenite.[1] There are no active volcanoes along this line,[2] and the old volcanic stocks are pretty well eroded.

There is a considerable stretch of alluvial running from Subig northwest to San Narciso. This stretch of country here is very dry in certain seasons, and owing to the composition of the soil the water sinks in rapidly and the whole appearance of the country is very much like that of the desert in the western part of the United States—particularly on the western slope of Pinatubo. For a

[1] The effect of the geology upon geodetic calculations was very effectively demonstrated recently in this part of Luzon. A considerable discrepancy between the astronomically determined points and the trigonometric stations near Olongapo was found to exist. The small Cinco Picos Range, which consists of pyroxenite, lies to the west of the stations and the great andesitic mass of the Zambales to the eastward. The observers expected the plumb bob to be deflected in an easterly direction owing to the main mountain mass being to the east, but the deflection was in the opposite direction toward the smaller mass. Not until an examination disclosed the denser rock in the Cinco Picos (to the west) could the discrepancy be explained.

[2] It was reported by Mr. Snyder of the Bureau of Lands that smoke was seen issuing from the top of one of these peaks.

more detailed description of this country, the reader is referred to Vol. IV, sec. A, No. 1, p. 19 of *The Philippine Journal of Science;* "Contributions to the Physiography of the Philippine Islands," IV, W. D. Smith.

We have, more or less, general notes on the population of this region but our main source of information comes from Reed who wrote quite extensively on the Negritos of Zambales. These people are pretty much the same as the Negritos of other parts of the Island, and make up a very much scattered and nomadic tribe.

The principal pass across this region is from O'Donnell in the Central Plain, to Iba. The government has built a road, within recent years, between these points.

There is another well-defined trail from Mangatarem across to Infanta at the southern end of Dasol Bay.

There is also a good road from Alaminos to San Isidro, and in the southern part there is a telegraph line from Olongapo to Dinalupijan. With the exceptions of the use by the natives and occasional expeditions of U.S. Marines, this trail is very little used.

The northern Zambales are not covered with a particularly heavy growth of timber; in fact, many parts, like Pinatubo are quite bare up to about 5,000 feet—the last 1,000 feet being covered with a dense mossy forest; this is due to the excessive moisture from the clouds which continually hang about the summits. In Bataan Province, the vegetation is very dense and the forests possess considerable commercial value. The Cinco Picos Range, however, is almost bare.

The southeastern volcanic cluster.—In northern Ambos Camarines, as I have already mentioned, the Cordillera bifurcates: one fork running through the Caramoan Peninsula, and the other following the west coast. Between these two in what was originally a more or less level plain, there has been built up a cluster of volcanic cones more or less dissected by erosion. However, there is one very perfect cone, Mount Mayon, which is probably the most perfect volcanic cone in the world. This is the highest of the group, and is only a short distance from Legaspi. What must have been a larger cone at one time, is now represented by Mount Isarog; but the symmetry of this has been destroyed by one side of the

mountain sliding out, so that there is a great gap in the crater on one side. In spite of the great size of these mountains and the deep canyons on their slopes, they are of very recent origin. Recently Adams, who made a trip through that country, has compiled all of the various reports in a very interesting and able discussion in his "Geological Reconnaissance of Southeastern Luzon," which is found in Vol. VI, No. 6, *Philippine Journal of Science*. Of all the travelers through this district, Martin, the government photographer, is the only one who has brought back good photographic records.

In 1909, Mr. Martin and a Franciscan Father from the town of Tobaco, made an ascent of Mount Mayon and secured fine pictures of the crater and of the country as seen from the crater. The most interesting point in connection with Mount Mayon, is, that the curve of its slope is so perfect that it can be represented by the formula for the sine curve:

$$\frac{4}{c}=\frac{e^{-x/c}c^{-x/c}}{2}$$

when $c=8.6$ mm.

This was worked out by Dr. G. F. Becker of the U.S. Geological Survey, who made a geological reconnaissance of that region in 1901.

An extensive population is found at the foot of these mountains, but in the higher parts there are only a few Negritos.

This district is one of the finest in the Islands, from a scenic point of view, as well as agriculturally, and occasionally, as in 1900, very spectacular eruptions take place from Mount Mayon.

Further south in Sorsogon is another large dissected volcanic stock called Mount Bulusan. This is very much like Mount Isarog in general appearance.

THE RIVERS

There is a host of rivers of all sizes in Luzon. I shall, however, refer to eleven only. The largest river is the Cagayan in the northern part of the island, the shortest, perhaps, is the Pasig, but from a human standpoint, the Pasig is by far the most important of all.

The Cagayan.—This river rises at about latitude 16°, and empties at Aparri, N. 18° 30′. Apart from local sinuosities it is a remarkably straight river, leading one to believe that it must follow some

structural line. This river is navigable up to Ilagan, and along its banks are located the principal tobacco fields of the Islands. At Aparri considerable difficulty is experienced from the formation of bars crossing the river mouth. The insular government is spending considerable money in keeping this channel open. This stream flows in a very wide, level plain and the soil is remarkably rich.

The Pampanga.—The second largest river of Luzon is the Pampanga. This river rises in the Caraballo Sur Mountains or in the "Central Knot," and flows somewhat west of south and debouches into Manila Bay, by means of a myriad of channels. This river is navigable for a long distance into the interior, and is one of the principal highways of commerce in Luzon.

The Agno.—The Agno river rises on the slopes of Mount Data in north central Luzon, and flows due south until it reaches the Pangasinan Plain where it turns sharply to the northwest and empties into Lingayen Gulf. This river is navigable for a short distance from its mouth, but in the mountain district is simply a roaring torrent washing along big bowlders, and is not at all navigable. This river overflowed its banks twice during 1911, flooding a large section of Pangasinan Province.

The Abra.—The Abra rises also on the slopes of Mount Data, then turns abruptly to the north, flowing for 40 miles or more until it gets to the town of Dolores, where it makes another very sharp bend and flows southwest, emptying into the ocean near Vigan. This river throughout a great deal of its extent is located in a deep gorge. Very little is known of the geology along its course.

The Bicol River.—The Bicol River where it rises due west of Daraga is known as the Kinali River. Thence it flows northwest along the Albay central plain, through one lake (Lake Bato) and a large swamp, finally emptying into San Miguel Bay. This river is navigable almost to Bato Lake. It very frequently overflows, and for this reason, the district through which it flows is one of the principal rice districts of the Islands.

The Angat River.—The Angat River is referred to here more on account of its length, than for any other reason. It rises in the Eastern Cordillera, flowing with considerable sinuosity westward, and empties into the Kingwa River which also flows across the

Bulacan Delta into Manila Bay. This river is not navigable to any great extent, but at Norzagaray the river has some falls where considerable power could be obtained.

The Bued River.—The next river in point of size is the Bued River, which, while much shorter than the Agno, flows in the same direction, and is only mentioned here, because of its connection with the famous Benguet Road. This river is probably responsible for more damage to the works of man than any other river in Luzon.

During the summer of 1911, it was the scene of a very destructive flood, which was due to a cloudburst, near Baguio. Thirty-seven inches of rain fell in twenty-four hours in Baguio. The larger part of this water flowed into the Bued River Canyon, and at the lower end, there occurred a great landslide which dammed the stream to a height of 60 feet. When this dam broke, a large portion of the lower end of the Benguet Road was washed out into the Pangasinan Plain. This road has suffered repeatedly from these floods.

The Pasig River.—The Pasig is a very short river, 15 miles, very deep and of moderate width, and is the outlet of Laguna de Bay. It is important mainly because of the great volume of commerce which travels along it, and for the fact that the capital of the Archipelago is situated at its mouth. This river is tidal in its lower section, about up to Fort McKinley. From here on to the lake, it is much narrower and quite shallow in places. The river has a very treacherous current.

The Paracale River.—The Paracale River is mentioned here not on account of its size, but because it is distinguished by two very important features. The most important is that it is probably the richest river of all, there having been discovered considerable stretches of rich gold placers along its course. From a physiographic point of view, it is interesting, because, in its lower portion, this river is a drowned river. It has long been known that the Camarines coast is subsiding.

THE LAKES AND SWAMPS

The true lakes in Luzon are first and foremost, Laguna de Bay; second, Taal Lake; third, Laguna de Canaren, Bato and Buhi, while the following, Paway, Cagayan, Pamplona, Mangabol, and Candaba are merely great swampy areas, whose size changes with the seasons.

Fig. 3.—Taal Lake; Taal Volcano on low island in right background

In his study of the Southwestern Luzon region, Adams has discussed the two first-named bodies.[1]

Laguna de Bay is a heart-shaped body of water with two prongs of land projecting into it from the north side. It lies a short distance southeast of Manila, and is separated from Manila Bay by about 6 miles of land. Its dimensions are 25 by 28 miles. It is fairly shallow. The height above sea-level varies between 0.9 and 4.3 feet.

Taal Lake.—The second largest lake in Luzon is Taal Lake or Laguna de Bombon (Fig. 3). This has generally been regarded as a crater lake by such writers as von Drasche and Becker, but Adams who has perhaps given more time and study to it than any other, attributes the origin of the lake to peripheral faulting. My own opinion is that the lake has originated through (1) peripheral faulting, (2) explosion of a former and much larger volcano than now exists there, and (3) subsequent collapse of the crater area (Fig. 4).

For details about this lake and volcano, I shall merely refer the reader to the three most exhaustive articles on this subject.[2]

THE HUMAN RESPONSE TO PHYSIOGRAPHIC CONDITIONS

The relationship between man's work and physiography, has long been emphasized by many writers. Although this relationship has often been over-estimated,

[1] G. I. Adams, "Geologic Reconnaissance of Southwestern Luzon," *Philippine Journal of Science*, V, No. 2.

[2] G. I. Adams, *op. cit.;* W. E. Pratt, "Eruption of Taal Volcano," *Philippine Journal of Science*, VI, No. 2; D. C. Worcester, in *National Geographic Magazine*, 1912.

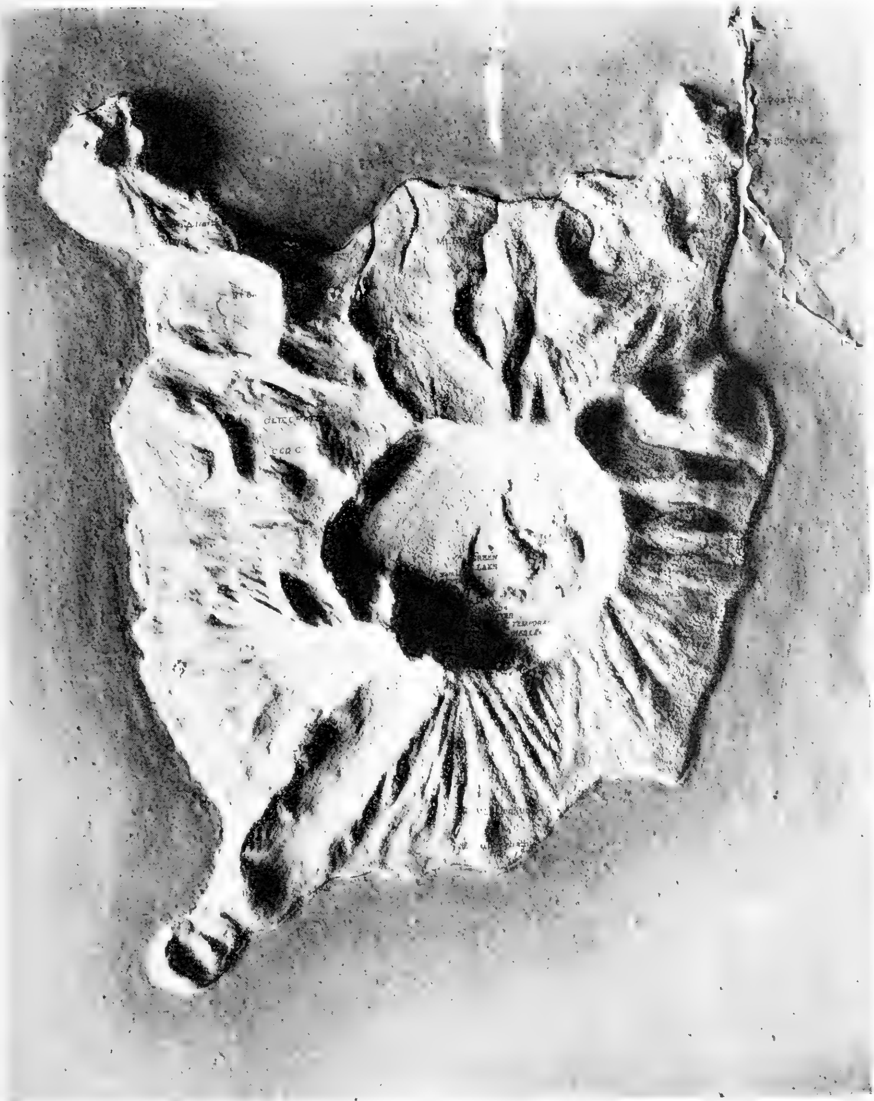

FIG. 4.—Photograph of model of Taal Crater as it was before the great eruption of January, 1911.

many things having been explained as due to the topography of the country that have really been very little affected by it, still it is certain that physiography is a factor of considerable importance. We know as yet too little about the wild tribes of the Philippines and too little of the topography of the country, in some parts, to make it safe to dogmatize much at this time. However, a few general statements may be made, which are to be taken as tentative, and (like a railroad schedule) are subject to change.

If we examine again the census map alluded to above, we note that there are certain dominant tribes in Luzon. In the north central region, the part occupied by the Cordillera Central, the dominant tribe is Igorot. In only one place does he come down to the coast, and that is where the Cordillera itself reaches the coast.

Next to this tribe, and almost completely hemming it in, are the Ilocanos, a rapidly increasing tribe and probably the most virile of all the tribes in the Philippines. It occupies the Coastal Plain, but has already gained a foothold in the Central Plain. Since the opening up of new roads and trails in the mountainous area, he has begun to wedge his way into the territory of the Igorot.

Occupying the "Central Knot" and adjacent mountainous country, we find the Ilongots.

The Negrito has been pushed back into the more or less unknown and inaccessible tracts, such as the Zambales and the southern Cordilleras.

Surrounding Manila Bay and extending down into Tayabas, we find the Tagalog. It is yet too early to state definitely, but it would seem that the Tagalog is becoming more and more restricted.

The southeastern peninsula is occupied almost exclusively by the Bicol, but here again in the almost inaccessible parts are to be found the Negritos.

Around Lingayen Gulf there is a small area occupied by the sub-tribe known as Pangasinans.

A recent writer on ethnological subjects says, that if a Bontoc were dressed in the clothes of the Tagalog and the Tagalog (un-) dressed like the Bontoc, it would be very difficult to note the difference. This is my own opinion about these people and I believe that the differences are very superficial. As soon as the

railroad and the school have had a chance to work on these people and mix them up, the tribal characteristics will largely disappear. At the present time it seems that the following characteristics may be noted with reference to the different tribes:

The Ilocano lives on the Coastal Plain and spends a great deal of his time at sea, as the Coastal Plain is too narrow to furnish all of the food necessary. He is, because of this life a nomadic individual and has therefore been able to penetrate farther into the other districts in Luzon. I expect to see this tribe, in time, dominate Luzon.

The Igorot is a much stockier man than the Ilocano, and shows, in his build, the effect of his hill-climbing life. Due to the mountain barriers, he has been kept more isolated and has to spend more time getting his food, and therefore is more of a stay-at-home. Many of the Igorots will not leave their own communities, being afraid to go from one town to another. The government is dispelling this vague fear of the Igorot, and many barbarous customs, such as head-hunting, are fast becoming obsolete. It is believed that the physiography of the country has had a direct and very important effect upon the people. Traveling in that country is a serious matter, and they will not take the trail, unless they are very hungry or some other inducement is offered.

The Negrito is very evidently a vanishing tribe. The government by its paternalism may for a time postpone the extinction of these people, but the arrest in their development seems to have been so complete that it is a question whether they can ever recover, or whether it would be of any particular value to the human race for them to recover. The writer has been among these people, and while he has seen some signs of an organized life, it is a hand-to-mouth existence, and they are often little better than animals. They are exceedingly shy and one may travel for days at a time through their country without seeing anyone.

The Tagalogs are the most advanced in western civilization, of all the tribes of Luzon, and a glance at the map will show how they have clustered about the capital of the Archipelago. Physically not much can be said of them. They do not produce very much of their own food, being mainly engaged in the more sedentary pro-

fessions. Whether the new form of education being introduced into the Philippine Islands will regenerate them, remains to be seen. It is a notable thing that they occupy only about one-third of the Central Plain of Luzon. The Ilocano, Pangasinan, and the Pampangan are fast crowding them back toward Manila. Some might argue that physiographical conditions are responsible for the political dominance of the Tagalog. But this connection is only an indirect one. The chief Spanish settlement of the Archipelago has always been Manila. Of course, Manila's situation depended upon physiographic features, and the Tagalogs happened to be where the Spaniards first settled, and in that way they have obtained their political pre-eminence, but it has been rather through the relationship to the Spaniard, than to the fact that he is living along the Pasig River and around Manila Bay.

The Bicol is a hard-working and very peace-loving individual, and is a man of the fields. It is not believed, however, that he will materially increase his present range.

Another tribe which appears to be peculiarly influenced in its habitat by physiographic conditions, is the Cagayanese. He is confined exclusively to the Cagayan Valley and the Batanes and Babyanes Islands directly north of Luzon.

We also note another feature in connection with the distribution of tribes: that the densely forested areas are occupied by the Negritos, the forests furnishing additional means of concealment.

What future changes will take place in the distribution of these people can only be conjectured. It is my opinion, that the Tagalog will follow new railroads and new highways. The Ilocano will probably dominate all of the lowlands, because he is a great rice grower. The Bicol will probably remain stationary, and the great stretch of country now covered by the Igorot will be criss-crossed by the paths of the Ilocano. All through this population will be found scattered, the Chinaman, as in all the countries of the Orient. He is not a producer, however, but occupies in the Malay world the same place as the Jew in the Western World. Outside of the large cities, the Chinaman controls the trade. As the government has placed severe restrictions upon the Chinaman, he is not now a very important factor. He affects the population to a certain extent,

by intermarriage with the natives, but the Chinaman as a Chinaman need not be considered further in this article.

GEOLOGY

GENERAL CONSIDERATIONS

If we examine the general geological map of the Island of Luzon, we distinguish in the southern part, a rough lining up of formations into belts or long strips having a northwest–southeast trend.

First, at the extreme southeast, there is a zone of metamorphic rocks beginning on the small island of Rapu-rapu and extending northward through Ambos Camarines in the vicinity of Mambulao. Their continuation will undoubtedly be picked up some day along the east coast of Luzon, farther north.

Next, to the westward, is a belt of recent volcanics. In this belt, are the well-known cones of Bulsan, Mayon, Iriga, Isarog, and the pretty well worn-down stock of Bagacay.

Third, the narrow Albay Plain.

Fourth, a broader belt of folded sediments in the western part of the Sorsogan peninsula, and constituting practically the whole of Tayabas peninsula. This belt continues up into Central Luzon, where it becomes partially concealed by later volcanic flows.

Fifth, another volcanic zone which takes in Taal, Talim and Arayat, in the eastern portion of the Central Plain.

Sixth, the plain belt, beginning with the Cavite Plain and the Central Plain, extending north to Lingayan gulf.

Seventh, the line of andesite stocks constituting the Zambales.

Eighth and westernmost, the very basic and dense rocks of the Cinco Picos range, just west of Subig Bay. This last is really almost insignificant in area, but very important as has already been mentioned.

In the northern part, we cannot, as yet, make such clean-cut separations, owing largely to our ignorance. However, a rude parallelism of belts can be made out.

Having considered the distribution of formations geographically, let us now turn to a consideration of the stratigraphic sequence; this is best shown by the tabular scheme in Table I.

The absence of older formations than the Tertiary from this column may be explained by one or more facts, namely:

TABLE I

TABULATED SCHEME OF STRATIGRAPHY

Period	Formation	Type Locality	Distribution	Economic deposit	Characteristic fossil
	Coral reefs	Cebu	Along much of the Philippine coast line	Building stone and lime	
	Littoral deposits	Sangley Point	Southern Luzon, Ilocos Norte	Sand	
Recent	Volcanic tuff	Vicinity of Manila		"Guadalupe" stone for building	Leaves, probably belong to *Euphorbiaceae*
	Basalt and andesite flows	Mount Arayat and Mount Apo			
Unconformity					
	Raised coral reefs	Cebu, west coast	Cebu, northwestern Luzon		*Hindsia dijki* Mart.
Pleistocene and Pliocene	Marls	Ilocos Norte	Samar, Agusan River		
	Eruptives	Mount Mariveles	Mindanao, Luzon, etc		
Unconformity					
Miocene	Limestone—upper	Cebu		Burned for lime, very pure	Shells very similar to recent forms; chiefly coral reefs
Unconformity	Andesite flows	Do	Cebu, Masbate, etc	Gold, silver, manganese, lead	
	Limestone—middle	Do	Cebu, central Luzon, southwestern Luzon, north Mindanao, east Mindanao, Romblon	Romblon marble, Montalban limestone	*Lepidocyclina insulae-natalis* Chap.; *Lithothamnium ramosissimum* Reuss. *Cyloclypaeus communis; Orbitolites,* etc.
Miocene	Sandstone	Batan Island		Oil in Tayabas and Cebu	
	Shale	Do		Coal deposits, Cebu, Batan, Polillo, Masbate Mindanao, Luzon, etc	*Arcas, Callianassa dijki* Mart.; *Vicarya callosa* Jenk.
Oligocene	Limestone—lower	Cebu, Batan Island			*Nummulites niasi* Verb.
Age uncertain, probably Tertiary	Crystalline schists, granite, gneisses	Camarines	Camarines, Ilocos Norte, Cebu, Zamboanga Peninsula, Romblon Island	Gold, mica, talc, apatite, hematite, magnetite	
	Iron formation	Bulacan			
Unconformity (?)					
	Radiolarian cherts	Ilocos Norte			Sponge spicules and fragments of Radiolarian tests
	Quartz porphyry	Lepanto	Central and northern Luzon	Copper ores	
Pre-Tertiary (?)	Diorites	Benguet	Northern Luzon, Leyte, Panay	Gold tellurium, silver	
	Gabbros	Leyte	Leyte, Mindanao, etc	Serpentine and asbestos	
	Pyroxenite	Ilocos Norte	Ilocos Norte, Zambales Mountains, Batan Island		
	Peridotite	Near Olongapo			

1. Very little exploration has been carried on in the dissected areas of northern Luzon, where we would expect to find the older formations.

2. The Philippine Islands are situated at the outer edge of the Continental shelf, where the sediments are all recent and the older rocks would naturally be very deeply buried.

3. Erosion has not as yet progressed very far, owing to the comparatively short period that the archipelago has been above the sea.

Below are given two sections across Luzon at different latitudes (Fig. 5. Infanta to Tanay [Ickis], and Fig. 6. North Central Luzon [Eveland]).

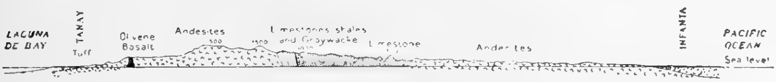

FIG. 5.—Section from Laguna de Bay to the Pacific. (After Ickis.)

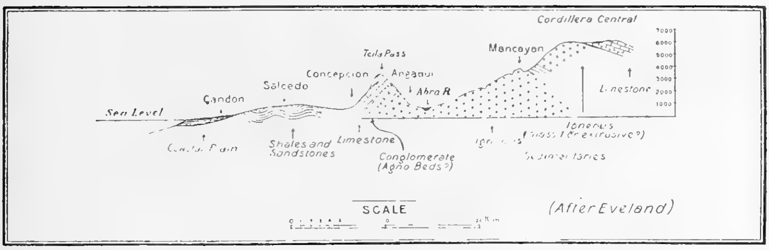

FIG. 6.—Section across North Central Luzon. (Eveland.)

THE IGNEOUS COMPLEX

By the igneous complex, we mean all those igneous rocks overlaid by the tertiary sediments, some of these are diorites, some andesite and diorite intrusions and others are granites. They are naturally encountered over larger areas in northern Luzon, where erosion has been at work longer and more vigorously. The central Cordillera then is the principal habitat, if we may use the term in this connection, of this class of rocks. Farther south, particularly in the vicinity of Manila, these rocks are deeply buried and only appear in isolated localities as in Ambos Camarines, the Loboo Mountains of Batangas, etc.

Diorite, quartz diorites, metadiorites, granites, gabbros are all found in Luzon. Diorite is the commonest deep-seated rock.

There is complete gradation from this rock into andesite, the difference between the two being chiefly one of depth and hence rate of cooling of the original magna.

As Professor Iddings has worked over most of the rocks in our Philippine collection, I shall refer the reader to his descriptions of these rocks.[1]

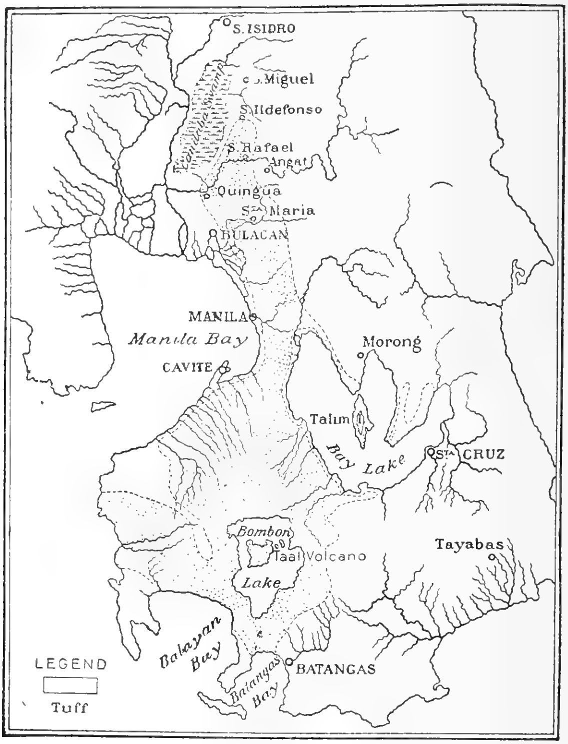

FIG. 7.—Map of Southwestern Luzon. (After Centeno.)

The extrusives.—As far as we now know, the andesites form the more or less worn-down volcanic stocks, and the basalts represent distinctly later flows. The andesites and basalts are generally fairly uniform, but we have besides, vast areas of volcanic agglomerates grading from a formation made up of large blocks more or less angular and somewhat scoriaceous, to a rather fine-grained tuff.

[1] J. P. Iddings, "Petrography of Some Igneous Rocks of the Philippines," *Phil. Jour. Sci.*, V, No. 2, 155.

Iddings, Oebbeke, and the writer have described specimens of these rocks from various parts of the Islands, but Iddings is the only one who has attempted anything like a systematic study of them, with a view of drawing conclusions concerning petrographic provinces, correlation, etc. He found that pyroxene andesites with hypersthene and augite both present predominate, next hornblende-pyroxene andesites, and third, hornblende andesites without pyroxenes, and last, a few with biotite in addition to the minerals already named.

There is a complete gradation from the andesites to the basalts. Some of the latter are extremely rich in olivine.

Dacites have been found in a few localities, Corregidor Island at the entrance to Manila Bay being the type locality.

The greatest distribution of agglomerates and tuffs is to be found in the region of Laguna de Bay and over a large part of Batangas Province (Fig. 7). The agglomerates are especially well shown in a deep and very picturesque gorge at Pagsanjan, Laguna, and from there all the way to Mount Banajao, one finds nothing but volcanic agglomerate with patches of tuff here and there. This tuff and agglomerate have been more particularly discussed by Adams in the article already referred to.

THE METAMORPHIC ROCKS

Metamorphic rocks have been found in Ilocos Norte, in Ambos Camarines and in Benguet, probably in many other parts they will be found when more exploration has been carried on.

In Ilocos Norte, we have actinolite and mica schists, bordering a granulite dike, in Benguet marble, due to diorite intrusion, in Ambos Camarines gneissic granite and schistose diorite.

The rocks of the volcanic mountains are by far the most widely distributed[1] of all the rocks in Southern Luzon, and possibly in the Island as a whole. The country surrounding Manila and southwestern Luzon is the principal home of these rocks. The chief centers are Arayat, Taal and Banahao, Mariveles, and the southwestern volcanic cluster. The principal rocks are andesites with later flows of basalt.

[1] For general distribution of the major formations the reader is referred to the map in *Regionale Geologie* (Steinmann in Bonn), VI, pt. 5, by Warren D. Smith.

THE TERTIARY SEDIMENTS

We have found in Luzon, so far, no sediments known with certainty to be older than the Tertiary. In Ambos Camarines, there is a brecciated sandstone, and a shale, which some have thought to be older, but fossil evidence is entirely lacking. In Ilocos Norte, on the Baruyan River, I found some outcrops of a very red brecciated jasper, which may represent a Jurassic formation. I made thin sections of this rock, and, while I made out no definite fossil forms, Dr. Karl Martin of the Reichsmuseum in Leyden, who examined them, said he could distinguish the remains of sponge spicules, and fragments of radiolarians, and he was of the opinion that the rock was very similar to specimens he had found in the Moluccas and which he had called Jurassic. These are exceptional and isolated cases. The main bulk of the marine sediments of Luzon are Tertiary sandstones, shales, and limestones. The sandstone is usually a fine to coarse-grained grey rock which is very impure, having, as a rule, more feldspar and ferromagnesian than quartz fragments. Just how thick it is, we have never been able to determine, through lack of good sections. It probably varies from 60 to 325 feet in thickness. The shales are bluish-black to light yellow, very fine-grained, and generally low in silica. There is every gradation between the sandstone and the shale. The shales lie over and above the coal seams at nearly all the outcrops. How thick these are, we do not know exactly. They usually are very thin-bedded and are not very consolidated. Above the sandstones we find a hard, white, crystalline limestone which contains abundant remains of foraminifera—the principal genus being orbitoides. Below, I insert Professor Douvillé's classification of the Philippine Tertiary, as worked up from material which I furnished him in 1908. This table (Table II) may fairly well represent the stratigraphy of Luzon. The uppermost limestone is noteworthy for its purity, as it has been changed very little since its formation in the sea. Coral remains are very abundant in many parts of it, in fact at an elevation of nearly 5,000 feet in Benguet we find a fossil coral reef containing fragments of many species of coral, most of which are now growing in the China Sea.

TABLE II

(AFTER DOUVILLÉ)

		Philippines			Borneo	
	c	Upper limestone with *small* Lepidocyclines	*Lep. c.f. Verbeeki miogypsina*	H	Burdigalien	
2	*b*	Sandstone and shale	*Clycoclypeus communis, Orbitolites alveolinella Miogypsina*	G F	Aquitanien	Miocene
	a	Middle limestone with *large* lepidocyclines	*Lep. insulae-natalis, formosa, richthofeni*	E		
1		Lower limestone with nummulites, Coal Measures	*Nummulites niasi Verb., Amphistegina c.f. Niasi, Lepidocyclina*	D	Stampien	Upper Oligocene

RECENT FORMATIONS

Under the recent formations, I shall take up the following: (*a*) Piedmont deposits; (*b*) coral reefs; (*c*) pyroclastics; (*d*) placers; (*e*) laterite, and products of weathering.

In a region of such tremendous rainfall, such as we have in the Philippine Islands (45 inches in twenty-four hours, recorded at the Baguio Observatory, Mountain Province, Luzon, July, 1911), probably nowhere exceeded save possibly at Simla in India, it is natural to expect great erosion in the high levels, and a deposition of the eroded material in great volume at the foot of the mountains. Such deposits can be found in Pangasinan Province, where the Agno and Bued River flow out onto the Central Plain, and along the western coast in the Ilocano Provinces. A great deal of the coastal plain of Ilocos Norte and Ilocos Sur is built up by this wash material, brought down by the short and rapid mountain streams. A great deal of this deposit consists of huge bowlders which are of considerable annoyance to farmers, and are serious obstacles to gold dredging, but with these bowlders comes down great quantities of finer material, which must play a great part in enriching the soil.

Coral reefs.—An examination of the coast and geodetic charts now issued for the coast-line of Luzon, show that there are great stretches of coral reefs. They are very important not only from the point of view of navigation, but they represent the foundation for the lateral growth of the island-mass. My own observations on the west coast of Luzon reveal the fact that much of that coast is now rising, and as the coral reefs grow up to a limiting plain—the

surface of the water—they naturally present, when elevated, a more or less flat platform upon which the rivers deposit their loads and in that way build up new land. On the east coast, it is not so easy to see this growth, as throughout much of its extent, the coast is sinking: witness the drowned river-mouths of the Paracale and other important rivers.

The Pyroclastics.—The present eruptions and those of the Pleistocene have generally been marked by great quantities of ash and rarely by out-pourings of lava. A great deal of this material happened to fall into the sea or other bodies of water and was subjected to a sorting process and as a result, we get the great beds of tuff so well developed adjacent to Manila. These beds alternate with marine sands showing rapidly changing conditions.

This tuff has been experimented with and found to be of practical value in the making of a variety of sandlime brick.

The greatest development of this, as has already been mentioned, is around Laguna de Bay, near Manila.

Placers.—On the east coast of Luzon in the vicinity of Paracale, Ambos Camarines, there is a considerable development of rich placer ground. The country is notable for the great number of "stringers," rich in gold, most of which are too small to work on an extensive scale, but where they have been eroded and the detritus has become concentrated in pockets in some of the "drowned," valleys on that coast, some remarkably rich ground has resulted. Gold and native copper as well as galena and sphalerite are found in them.

In the streams near Manila, principally the Mariquina, some platinum has been found. Along the Bued River also are promising placers.

Laterite, etc.—Naturally the action of weathering in the tropics is very important and very pronounced, but on the higher lands, it is not always so evident, because the tremendous rainfall quickly removes any unusual accumulation of material.

The great development of ferro-magnesian minerals in the igneous rocks, results in an extensive accumulation of iron rich soil on the lower slopes, and this is so often like the deposit known as laterite, as to merit special mention as a distinct formation.

Much that passes as laterite in the East is undoubtedly merely a product of weathering of rocks, in place, though it is recognized that there is more than one mode of origin.

ECONOMIC

COAL

No workable coal seams have been yet opened upon the Island of Luzon, though in Spanish days, some pretense was made to work some seams at Bacon in Sorsogón Province. At this place, the seams appear to be continuations of those on Batan Island. The Spanish engineers had opened up these seams with several hundred meters of galleries.

Coal has been found at several other places on the mainland, in the sub-province of Bontoc Ilocos Sur, Rizal, Bulacan and Tayabas, but either in too small seams, or in unfavorable localities.

However, on two islands, so near the Luzon coast as to be practically a part of that island, namely, Polillo and Batan, workable coal seams have been prospected and partially developed for some time.

Batan Island.—The East Batan mine, which is located on the East end of Batan Island, consists of several hundred feet of underground workings on a seam of coal about five feet thick. The main entry to this mine is about 1,500 feet long, and runs in on the coal seam, at an angle of 42° from the direction of dip. The dip of this seam varies between 10° and 13°. The coal is a sub-bituminous coal with lignite qualities.

The government has erected at this mine large coal pockets and the coal is being used in the island steamers. Some development work was carried on on the western end of this Island by the United States army in former years, but it has now been abandoned.

Polillo Island.—On the eastern side of Polillo Island which lies in turn on the eastern coast of Luzon, there are four, probably five, seams of a very fair grade of coal. Two of these, possibly only one, will be found to be advantageously worked. These seams are dipping at a moderate angle toward the coast, but near the center of the Island where the coal measures abut sharply against the igneous rock, the seams are highly inclined, and in some cases vertical.

The development work is now in progress in that district. This coal is of somewhat better grade than the Batan coal. Coal has been found of a poor quality in a number of other places on the Island of Luzon, namely in Cagayan Valley, in North Central Luzon and in the sub-province of Abra, but no development work has been carried on there.

IRON

As the next most important mineral resource, we shall consider iron. This mineral in small quantities is wide spread. It is usually found associated with the crystalline rocks of the eastern Cordillera. It has been found in noteworthy quantities, in two districts, near Angat Bulacan and on a small island in Mambulao Bay, Ambos Camarines. It is quite probable that there is a fairly continuous belt of this mineral following the Cordillera between its two points. Magnetic Surveys to determine this, are now in progress by the division of mines, Bureau of Science.

At Angat, the iron deposits appear to be of considerable extent, but diamond drilling will be necessary to prove this. The ore is a very hard bluish hematite, which is found in the crystalline rocks, and is probably a segregation due to the alteration of chalcopyrite, and other iron-bearing minerals in these rocks. The natives here have mined and smelted this ore in a crude way for over a hundred years. No flux is used and charcoal is the reducing agent. The most successful of these iron workers is a native woman, Dona Maria Fernando, who sells about 15,000 plow shares and points a year, throughout the neighboring provinces.

Several engineers have examined the deposit in Mambulao Bay and it is the general opinion that there is a commercial quantity at that point, which can be worked from sea-level.

OIL

Petroleum has been discovered in seeps at several points in the Bundoc Peninsula in Tayabas Province (see reports by Adams, Eddingfield and others in the Mineral Resources of the Philippine Islands) and one well has been sunk to a depth of 140 feet. As yet, there is no commercial production and none can be hoped for, till deeper wells are bored. The whole country-side in that region has

been plastered with claims, by speculators and others, totally ignorant of the business or who have no money to carry on the necessary operations properly.

With a view to opening up this field, the government has begun triangulation in the district and later, this will be followed by topographical and geological surveys.

The oil is very light, having a paraffin base. It has a beautiful, clear, cherry color. An analysis is as follows:

ANALYSIS[1] OF OIL FROM WELL, NEAR THE VIGO RIVER

Specific gravity of oil at 15°5 C.	0.845
Initial boiling point	80 c.
First fraction, light oils, 70°–150° C.	27.0 %
Second fraction, burning oil, 150°–300°	56.75 %
Residuum above 300° C. by diff.	16.25 %

The formations here are Tertiary sandstone, shales, and limestones, flexed into a broad gentle anticline, with minor flexures, faults, etc., and is more or less intruded by igneous rocks.

Oil has been reported from other localities in Luzon, the chief one being near Aliminos in Pangasinan Province, but examination by members of the Division of Mines revealed no trace of oil. The formations there are, however, favorable for the accumulation of oil.

GOLD

In the very earliest records wherein the Island of Luzon is mentioned, there is also a reference to gold. When Magellan reached Cebu in 1521, he heard accounts of gold in that part of Luzon, now known as Ambos Camarines.

The natives of that province have a very pretty legend about how on a certain time, a golden carabao comes out at night from one of the mountains and passes under the sea to a neighboring mountain and how the gold deposits are in some way, connected with that carabao.

For centuries, the natives have panned for gold in their crude way, not unlike the methods employed by all primitive peoples, and they have even gone so far as to construct a crude and very limited

[1] Analysis by G. F. Richmond, Bureau of Science.

dredge, capable of handling a half-ton of gravel and sand in a day. Not only did the Tagalogs but all the tribes including the wild Igorots, pan gold and from nearly every stream in the island. I have never yet found a stream which did not carry some gold. This gold, won by the natives, usually finds its way into the hands of the Chinese traders, and consequently it is difficult to get even an estimate of how much is recovered annually, but I believe that one thousand ounces a month is a very conservative estimate.

In the early eighties of this century, there were scores of arrastres in operation in Ambos Camarines; but hardly a single one can now be seen. This method, with which all mining men are familiar and hence need not be described here, was introduced by Spaniards from Mexico, probably over two hundred years ago.

At the present time, there are only one or two arrastres working in the district.

Several attempts at mining on a large scale were made, prior to the American occupation, but all were futile. But with the inrush of American prospectors and renewed vigor and new hope in the country, the outlook for the mining industry became very bright.

The first modern stamp mill of any size was erected on the Benguet consolidated property and began operating in 1906, and in 1907, the first large dredge (New Zealand model) was placed on the Paracale River. There are now two dredges at work, one building and a fourth projected.

The mills have not been so successful, due to a variety of causes, chiefly inadequate capital and poor management. The lodes are of many kinds. In Benguet, they are usually quartz fissure veins in andesite, while some contact deposits between the sediments and andesite and diorite have been noted. The gangue is predominately quartz with or without calcite, manganese oxide, and rhodochrosite. The gold is in some veins free, but is usually found in the pyrite in a finely divided condition, so much so that the best method of treatment will consist of crushing in cyanide with stamps and fine grinding in tube mills.

In Paracale in Ambos Camarines, there is much more free gold and a large number of the veins are "stringers," which are very

tantalizing and have been the ruin of more than one over-enthusiastic miner. In these veins the gangue is mainly a cellular quartz. There is also enough zinc and lead to complicate the process of treating these ores. Very little manganese is to be seen in these veins and the striking fact to be noted here is this, that this is the best placer district so far found in the whole archipelago.

COPPER

Copper has been found in the form of arsenates and sulphides in the Mancayan-Suyoc district of the Mountain Province, Luzon and the Camarines. The best known deposit is that in the Mancayan-Suyoc district. Eveland[1] writes the following concerning this deposit:

> In view of the fact that the entire region, with the exception of the one ore body of the Mancayan mine, is in an early stage of development, it is impracticable to treat the ore deposits in detail. It seems to be fairly conclusive, however, that the general type of vein in the district is a narrow quartz lead, carrying metallic sulphides, in some cases of copper, and generally with gold associated in a free state. These veins are in the Mancayan diorite which underlies the entire district. With the advent of the "trachyte" flow, metamorphic changes have taken place and the nature of the country rock is altered to a considerable degree.

Recent development work has shown this deposit to be rather in the nature of a stockwork, and it appears to me to be more extensive than was first thought to be the case.

[1] A. J. Eveland, *Bulletin No. 4*, Min. Bur. Manila (1905). For further data regarding the mineral resources of the Philippines the reader is referred to the annual bulletin *Mineral Resources of the Philippines,* issued by the Division of Mines, Bureau of Science, Manila, P.I.

PRELIMINARY NOTES ON SOME IGNEOUS ROCKS OF JAPAN*[1]

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COMENDITE

This remarkable rock is found as blocks in a small stream running into the Bay of Iibi, a small village on the northeastern coast of Dōgo. The environs of the village consist mainly of schistose granitic rock and its porphyries, in association with rhyolites. Though the exposure of the comendite was not observed by the writer and its geological occurrence cannot be stated at present, it seems highly probable that the rock is a differentiated and effusive form of the same magma from which the above-mentioned rocks were derived.

Megascopically, the rock is light gray with a bluish tone and exhibits a distinct wavy flow structure, produced by the arrangement of feldspar crystals and lighter-colored crystalline bands, and has a tendency to platy parting under the hammer. Numerous phenocrysts are quartz and feldspar. The quartz is conspicuous, with rounded outline, and varies in diameter from 1 mm. to 3 mm. The feldspar is glassy, fairly well defined, and prismatic or tabular, from 1 mm. to 5 mm. in length, the prevailing length being 2 mm. Megascopic phenocrysts of colored minerals are rare. The groundmass shows a certain diversity of texture, some parts being aphanitic and compact, and some parts more crystalline and lighter in color. This property produces the fluxion structure already mentioned.

Microscopically, the constituent minerals are quartz, alkali-feldspar, arfvedsonite, barkevikite, aegirite, aegirite-augite, titaniferous iron, magnetite, and apatite. The conspicuous pheno-

* Published by permission of the Director of the Imperial Geological Survey of Japan.

[1] A continuation of Paper VI, on "Quartz-Syenite and Comendite from the Oki Islands," published in the issue of this Journal for October–November, 1912.

crysts are quartz and feldspar, the latter being more abundant. Besides these, there are present bluish-green and deep reddish-brown ferromagnesian minerals belonging to the pyroxene and amphibole groups. These are fewer and smaller than the colorless phenocrysts. The groundmass is strongly marked with flow structure, due to both the diversity of crystallinity and the arrangement of constituent minerals. The greater part shows a microfelsitic texture, essentially composed of quartz and feldspar, through which are scattered numerous small ragged shreds or mosslike patches of aegirite and aegirite-augite, associated with minute grains of magnetite. A microspherulitic intergrowth is also seen. Through this fine groundmass are coarser crystalline bands, mainly composed of feldspar and quartz with subordinate green pyroxene, developed in a lenticular form. The mode of development of these minerals exhibits some peculiarities. The minerals occurring in the marginal part of the lenticular area are arranged perpendicular to its outline, but those in the inner part show a micrographic or micropegmatitic arrangement.

The quartz phenocrysts are mostly subhedral, sometimes anhedral, with diameters varying from 0.05 mm. to 3 mm., but euhedral forms are also seen. The mineral contains several kinds of inclusions. Glass inclusion with or without a gas bubble is not rare. They are commonly bounded by crystal planes. There are abundant inclusions of groundmass material, showing irregular forms. Aegirite groups are also inclosed.

The feldspars are wholly alkalic, and almost all of them are possibly soda-bearing potash varieties, though a few crystals appear to be sanidine. The phenocrysts occur in two shapes, tabular or columnar, and are commonly subhedral. In some instances, the outline is strongly rounded and curved, and is deeply invaded by the groundmass. Some crystals have a regular shape, fairly well inclosed by crystallographic faces. The twinning observed is wholly Carlsbad, and no microcline structure is noticeable. The feldspar material is entirely fresh and is plainly marked by the cracks characteristic of sanidine. The plane of the optic axes appears to be perpendicular to (010). The acute optic angle (2E), measured on three thin sections, is 56° 34′, 50° 16′, and nearly

zero. The optical character is negative. Inclusions are common. The most abundant are of groundmass material, as is the case with

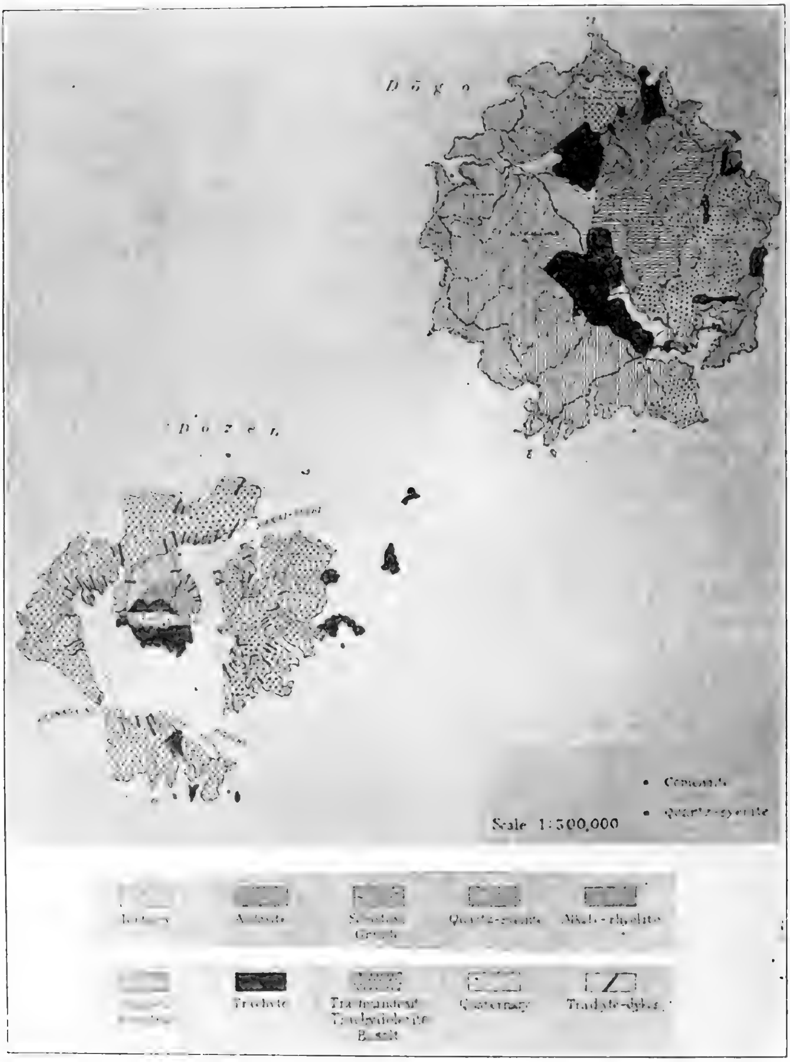

FIG. 3

the quartz phenocrysts. Quartz is frequently inclosed, and pyroxene and glass are also seen.

The ferromagnesian minerals belonging to pyroxene and amphibole groups are arfvedsonite, barkevikite, aegirite, and aegirite-augite. The amphiboles occur as phenocrysts, and the pyroxenes both as phenocrysts and in the groundmass. The phenocrysts of these minerals are usually found in association. Barkevikite occurs irregularly intergrown with the arfvedsonite on the one hand, and with the aegirite and aegirite-augite on the other. Their shapes are elongated or short prismoid, but their outlines are irregular and ragged. No cross-section was found in ten thin slices made for the purpose of determining the cross-section. So the determination of the optical orientation of the minerals was difficult. The aegirite-augite is distinguishable from the aegirite by its higher birefringence and larger extinction angle, reaching $c \wedge X = 37°$. From the aegirite, the arfvedsonite is distinguishable by the extinction angle and its direction, compared with those of the barkevikite associated with them. The aegirite extinguishes at a small angle or nearly zero in β, in which the barkevikite extinguishes also, while the arfvedsonite extinguishes in $-\beta$. On a longitudinal section, the extinction of the barkevikite was measured as $c \wedge Z = 2°$, and the arfvedsonite showed $c \wedge X = 15°$ in concurrent direction. Some crystals are strongly decomposed and are completely altered into a yellowish-brown substance. There are a few minutes rods to be identified as aenigmatite in the groundmass. They are deep brown or almost opaque.

Chemical character.—A chemical analysis of the rock, made by K. Yokoyama in the chemical laboratory of the Survey, compares fairly well with those of the comendites from other localities, described by different authors. It shows well its characteristic properties: high alkalies and nearly equal amounts of soda and potash, low lime and magnesia, fairly high iron oxides, and low alumina in proportion to alkalies and silica.

The analysis of the rock from the Oki Islands is given under column A in the following table, and is compared with those of the comendites from Comende, Sardinia (B)[1], and Iskagan Bay, East Siberia (C).[2] They resemble one another very closely, though

[1] H. Rosenbusch, *Elemente der Gesteinslehre*, 3. Auflage, p. 332.

[2] H. S. Washington, *American Journal of Science*, XIII (1902), 180.

the rock from the Oki Islands differs from the others in lower silica and in total and relative amounts of iron oxides.

	A	B	C
SiO_2	72.21	74.76	75.44
Al_2O_3	11.20	11.60	11.98
Fe_2O_3	2.25	3.50	0.88
FeO	2.66	0.19	1.02
MgO	0.08	0.18	0.10
CaO	0.27	0.07	0.33
Na_2O	4.29	4.35	4.06
K_2O	4.81	4.92	5.01
H_2O+	1.45*	0.64	0.68
H_2O-	....	....	0.13
TiO_2	0.44	Trace	Trace
P_2O_5	0.10	Trace	....
MnO	0.10	Trace	Trace
Total	99.89	100.21	99.63

* Loss on ignition.
A. Comendite from Iibi, Dôgo, Oki. K. Yokoyama analyst.
B. Comendite from Comende, Sardinia. M. Dittrich analyst.
C. Comendite from Iskagan Bay, East Siberia. H. S. Washington, analyst.

Norms of these rocks are given in the following table:

	A	B	C
Quartz	28.3	31.6	31.9
Orthoclase	28.4	28.9	30.0
Albite	30.9	32.0	33.0
Acmite	4.6	4.2	0.9
Diopside	0.5	....	....
Hypersthene	3.4	0.5	2.1
Magnetite	0.9	0.7	0.9
Hematite	....	1.6	....
Ilmenite	0.9	....	....
Apatite	0.3	....	....

From the above table, it will be seen that the rock from the Oki Islands is closer to that of Comende than that of Iskagan Bay and is richer in femic minerals than the other two.

The ratios of the Oki rock are as follows:

$\frac{Sal}{Fem}$ 8.26

$\frac{Q}{F}$ 0.48

$$\frac{K_2O' + Na_2O'}{CaO'} \ldots\ldots\ldots\ldots \infty$$

$$\frac{K_2O}{Na_2O} \ldots\ldots\ldots\ldots 0.86$$

By the *Quantitative System*, the rock may be classified under the name liparose, in which the other two comendites from Comende and Iskagan Bay belong also.

THE QUIZZYHOTA LACCOLITE

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EARLY REFERENCES

The first reference to this remarkable mountain that I can find is contained in a description of Kaffraria by the Rev. Francis Fleming:[1]

> But perhaps the most surprising and gigantic of these singular precipices, as yet known in Kaffraria, is that which rises on the south bank of the Great Kei River, about seven miles from the old military post of Fort Warden and lying fifty miles north of King Williamstown. It forms one side of a singular shaped mountain, the Quizzyhota.[2] The top is a long table-land of some miles in length, but contracted to about one or perhaps less in width. The extremities of the mountain and of the krantz which forms the whole north side of it and which is thickly covered with aloes, euphorbias and orchids, rise suddenly at angles of nearly 45°; the surrounding country stretching out into low undulating ground thinly dotted over with straggling mimosas and spec-boom, *Portulacaria afra*, gives an abrupt and most singular appearance to this object. On the southern side, which is thickly covered with large and thick bush, the hill descends with rather a more gradual slope and so affords an easy retreat for the Kaffirs.
>
> For the purpose of visiting this singular locality a party of six officers left their quarters during the war of 1846. (Theal gives 13th November, 1847.) One of the number, however, feeling indisposed, left their party a short distance from the camp and returned home and so escaped the untimely end to which the other five poor fellows came. These unfortunate and deeply lamented officers were: Major William Leinster York Baker, Lieutenant Clarevaulx Faunt, Ensign William Burnop (Adjutant) and Doctor Neil Stewart Campbell of the 73rd Regiment, and Doctor R. J. Locke of the 7th Dragoon Guards. The author who visited the spot in person to superintend (by request) the removal of the bodies to King Williamstown, made every enquiry while there respecting them and their death scene. One Kaffir was shown to him who displayed a wound on his right side which he said he had received from one of the gentlemen

[1] *Kaffraria and Its Inhabitants*, London, Simpkin, Marshall & Co. (1854), 39.

[2] *Quizzyhota* is a Kaffir word meaning "the place where one warms one's hands." The name is particularly applicable to the mountain as the middle slopes consist of bare faces of dolerite which, exposed throughout the day to the sun, absorb the heat and become intensely hot.

(probably Major Baker) whom he described as fighting most gallantly to the last and only killed by overpowering numbers. The author has also every reason to conclude that all were killed there and then and that no previous torture of any kind was attempted by the Kaffirs.

Two days had passed before their bodies were discovered and brought to Sir George Berkeley's camp then pitched on the banks of the Komgha stream, a small tributary of the Kei, about ten miles from the spot where they fell. Here they were hastily interred in one grave, but in the month of August, 1850, only a few months before the present Kaffir outbreak, the bodies were fortu-

FIG. 1.—Etanga Valley from railway. The Quizzyhota, showing the horizontal Karroo rocks above and the bare faces of dolerite below.

nately removed and reinterred in an unmolested and shortly to be consecrated grave beneath the western tower of Trinity Church, now in course of erection at King.

The woodcut of the scene accompanying Mr. Fleming's account is taken from about the thirty-second milestone on the newly constructed Amabele–Butterworth railway; this, and the fact that the Quizzyhota faces northwest, clearly identify the actual scene of the slaughter. Locally the abrupt mountain opposite the Quizzyhota and separated from it by the gorge of the Etanga,[1] which forms a much more prominent landmark from the level of the river, is

[1] *Etanga* is a Kaffir word meaning a "place where the cows are kept." The best cows are kraaled round the huts, but the surplus are sent out to some sequestered place, usually inclosed, as this particular valley is, by inaccessible cliffs, so that by merely fencing the narrow opening the cattle are prevented from wandering.

called Mordenaars Kop or the Murderer's Hill, but this is clearly incorrect.

DESCRIPTION OF THE QUIZZYHOTA LACCOLITE

The laccolite extends some 3 miles along the Kei River and it can be traced for some 6 or 8 miles into the plateau on which the village of Komgha stands. The plateau is some 2,000 feet high; the village which lies in a slight hollow is 2,114 feet above sea-level; the bottom of the cliff is 500 feet, so that the height of the vertical

FIG. 2.—The western end of the Quizzyhota laccolite, showing the vertical faces of the dolerite on the north and the undisturbed Karroo rocks in front.

face of the laccolite is 1,500 feet. The laccolite ends along the river in a vertical face which, however, is seen only in the western end and then for only a part, as the undisturbed horizontal sedimentary beds form three-fourths of height of the hill. Down stream, on the east of the Etanga Valley, the dolerite is exposed nearly to the level of the river bed, but there is always a little foot of sediments between the dolerite and the river; here unfortunately weathering has degraded the vertical face of dolerite to a slope of about 30° covered with gigantic bowlders, and it is impossible, therefore, to give a photograph showing the entire face. The rock

readily splits up along joints when exposed on the surface, and even the fresh face on the west, where it is exposed above the sedimentary beds, has scaled to a depth of some 10 feet or so; and the slopes below are covered with scree formed of the fallen blocks.

Along the Etanga Valley the dolerite comes toward the Kei River with a covering of 100 feet of sediments, then just below the farmhouse, on top, the dolerite breaks through to a higher horizon; at the western end there remains a covering of sedimentary

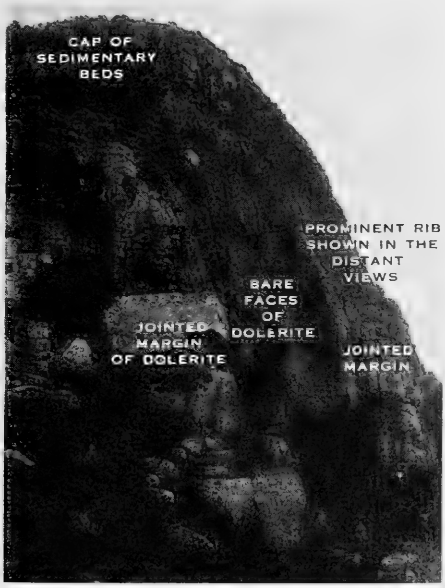

Fig. 3.—Western end of the Quizzyhota laccolite.

beds of about 30 feet thick, but on the Quizzyhota Hill the dolerite apparently reaches the summit. The line of demarkation where the dolerite impinges on the sedimentary rocks is exposed with extraordinary clearness on the krantz. The length of the laccolite along the river is cut twice by short valleys; the easternmost is the Etanga Valley, which is a deep fjord-like gorge that runs into the dolerite, doubtless along lines of original fracture which have been worked out by weathering. The valley forks into two branches about half a mile from the entrance. One of the branches

runs south and ends in a cul-de-sac surrounded by bare faces of dolerite; the other runs west. The bottom of the valley rises very gently and is about a hundred yards wide. It is surrounded everywhere by the dolerite; the new railway skirts the edge of the southern branch, and the view as one looks down into this cleft from the carriage window is most remarkable. The streams flowing down into the Kei from the escarpment of the plateau are very steeply graded, but here is a valley which begins at the head with a vertical wall 1,000 feet deep.

The laccolite is about three miles long from east to west, the exposed vertical side facing north, but there is a low-lying expansion of about 100 feet above the level of the river which is exposed in a cutting near the zig-zag of the railway, and this would add another mile to the length along the river. The faces of the main mass are quite vertical toward the river which comes almost due south to the laccolite, abuts against it, and follows its northern edge to the east. The sedimentary rocks are for the most part cleared away from the northern side. On the downstream end, above the hotel and road-bridge, the dolerite has been exposed for a long while and there is only a steep slope rising at an angle of 30°, studded with gigantic bowlders of dolerite, but for the rest grassy, with sparse mimosa trees. About two miles up the river is the Etanga Valley. On the west the dolerite rises in a magnificent vertical wall, capped with horizontal beds of sandstone for some 30 feet. On the outside of the vertical face there is a zone of much-jointed dolerite rising in pinnacles on either side of a sort of window of sedimentary rocks through which the vertical face appears. The pinnacles are the jointed outer margin of the laccolite. The dolerite to the west of this plunges into the sedimentary beds which form the walls of the valley of the Great Kei River lying almost at right angles to the northern face of the laccolite. In other words, the laccolite has barred the way of the river which flows at its foot, and the weathering that has allowed a small amount of sedimentary beds to remain plastered, as it were, on to the face of the laccolite on the west, has cleared all these away down stream on the east. In the same way the sedimentary beds form half the height of the hill on the west of the Etanga Valley, between the dolerite and the river, so that

at first sight it would appear that the actual base of the laccolite was exposed, but farther down stream the dolerite descends to the bed of the river. The sedimentary rocks in the bed of the river, though quite close to the dolerite, are unaltered and undisturbed.

The top of the laccolite spreads out to the south beneath the thin covering of sedimentary beds, perhaps reaching the village of Komgha which lies to the west-southwest about 10 miles from the bridge in a straight line (18 by railway). Three miles from the village, however, the railway skirts a shallow valley on the plateau which is covered with rich black soil, very different from the light sandy soil derived from the weathering of the sedimentary beds, which is good only for pasture lands; here, however, every inch is cultivated. This is the first exposure of dolerite which one can definitely connect with the Quizzyhota laccolite. The dolerite continues along the railway for 2 miles, then runs over the sedimentary covering for half a mile, and then again for about 200 yards is carried over the dolerite. Beyond, the railway cuttings are in the sedimentary beds forming a thin undisturbed covering to the laccolite, till the Etanga Valley is reached 2 miles farther on. Here the railway crosses the road at No. 6 railway cottage, and the plunge into the valley of the Kei begins. For a little distance the railway is cut in the eastern slope of the laccolite, which is here intensely weathered, the square jointed blocks having broken down into a brown sand, while in their centers there remain, in many cases, rounded blocks of quite unaltered rock. The blocks exposed in a similar position on the western end facing the river are jointed in the same way, but there is no evidence of the spheroidal weathering nor of the intense alteration. It appears that the intense crumbling is a consequence of the covering of sour soil which yields organic acids in large quantities and thus supplies a powerful solvent for the iron combined in the ferro-magnesian minerals. The finest example of the spheroidal weathering about here is in the great laccolite which lies 3 miles from Amabele Junction and which is exposed along the railway to within a few miles of Komgha village (27 miles from Amabele). Here the jointing is horizontal and vertical and every tenth block, more or less, has a solid unaltered core of grey dolerite. The weathered material can be dug with a spade and is

used extensively as fine gravel. The spheroidal weathering is noticed only on the outer margin of the laccolites. From the top of the Etanga Valley to the river level there is a drop of 1,500 feet; Komgha lies on the plateau at 2,114 feet above sea-level, and

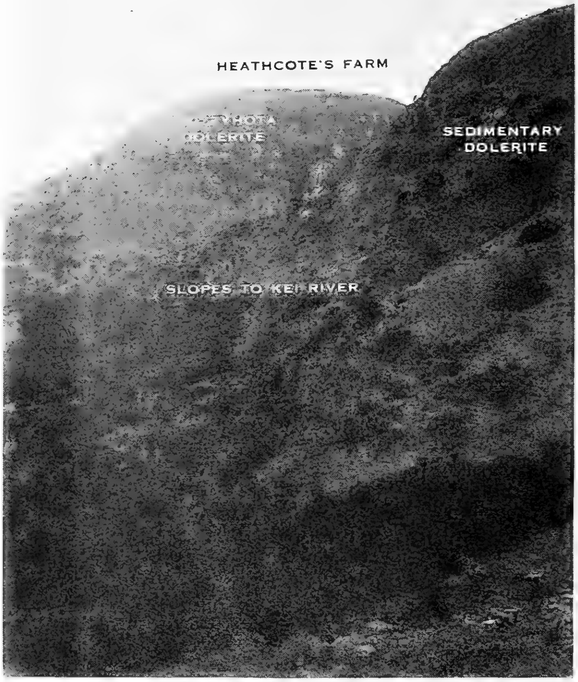

FIG. 4.—The Quizzyhota Mountain, showing the dolerite breaking up through the Karroo sedimentary beds. Looking east, i.e., down stream.

Sihota,[1] the station just on the Transkeian side of the bridge, at 560 feet. Sihota lies some 50 feet above the river. This drop of 1,500 feet is accomplished by the railway in 10 miles, or less than half that in a straight line, and just before entering the zig-zag by which the train reaches the level of the river there is a small expo-

[1] *Sihota* is a Kaffir word meaning an "ant-bear."

sure of dolerite in the cutting, which may belong to the main laccolite or may be a horizontal dyke proceeding from it, or may be quite an independent body; farther away there is an exposure of dolerite in the small valley crossed by the railway but the relationships of this and dolerite in the cutting are uncertain.

In the Amabele-Komgha laccolite the mass rears its head above the general level of the plateau which belongs to the 2,500-feet plateau[1] but which has been degraded by surface weathering some 300 to 400 feet. The Amabele-Komgha laccolite was below the level of the original plateau, although now its bald head is exposed; the Quizzyhota laccolite, on the other hand, is only just beginning to appear on the plateau, being for the most part hidden by the sedimentary beds.

THE SEDIMENTARY ROCKS INTRUDED BY THE QUIZZYHOTA LACCOLITE

The Sedimentary Beds cannot be placed in any definite scheme as yet. They consist of whitish or light grey-blue sandstones, fairly loose in grain, interbedded with blue shales, weathering yellow. They correspond to the Karroo Beds as exposed in the Free State and Transvaal and to which Dr. Molengraaff gave the name of "High Veld Series." Farther east, at Idutywa, the whiteness of the sandstones becomes more pronounced and the shales become brilliantly colored with red, purple, and blue tints, but the ordinary blue shales occur as well. Dr. Rogers and myself gave these beds the name of the "Idutywa Beds."[2] Subsequently Mr. Du Toit described the same beds from Queenstown and Burghersdorp districts as the "Burghersdorp Beds."[3] There seems no necessity to reduplicate names, and the term "Idutywa Beds" will be used here; eventually, if the connection is established with the Transvaal rocks, Molengraaff's term will have to be adopted. The suggestion to call them the *Cynognathus* beds, from the occurrence in them of this remarkable Theriodont reptile, does not appeal to

[1] E. H. L. Schwarz, "Coast Ledges in the South-West of Cape Colony," *Q.J.G.S.*, LXII (1906), 70.

[2] A. W. Rogers and E. H. L. Schwarz, "General Survey of the Rocks in the Southern Part of the Transkei and Pondoland, Including a Description of the Cretaceous Rocks of Eastern Pondoland." *Ann. Rept., Geol. Comm., 1901*, Cape Town (1902), 28.

[3] *Ninth Ann. Rept., Geol. Comm. 1904*, Cape Town (1905), 77.

me, because the fossils are extremely rare and localized, whereas the formation can be very clearly recognized by its lithological characters. Where the usual fine-grained blue sandstones of the Beaufort Beds proper give place to the coarser-grained white varieties, one can at once draw a line of division and map the latter as Idutywa Beds. The Idutywa Beds extend into the Western Karroo north of Laingsburg and far to the north in the Transvaal.

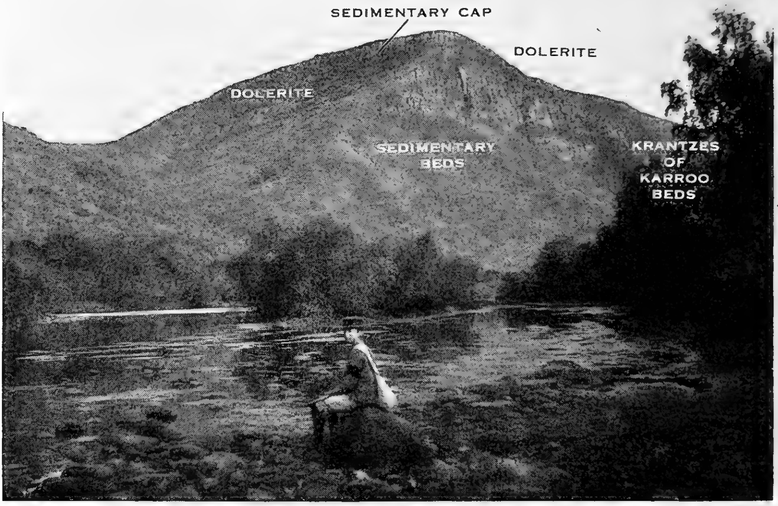

Fig. 5.—Western end of the Quizzyhota laccolite, showing the vertical face of the laccolite on the north and the sedimentary beds, plastered, as it were, onto the face, themselves quite undisturbed.

They once had a wider area of deposition than any other of the divisions of Karroo System.

Toward the middle of the descent of the Kei Hills the white sandstones disappear, and in their place there are the ordinary blue and blue-black shales, weathering olive-brown, which belong to the Beaufort Series. The normal sandstone banks of the formation farther west do not appear, probably because the weathering is so different. Here in the east, the country is a recently dissected plateau covered with grass and scored by deep ravines; in the west

the beds are exposed under arid conditions and the small differences of texture and hardness are very boldly shown on the faces of the kopjes. It may be that these differences are not sufficiently great to cause a separation into sandstones and shales in the sides of the ravines, where there is always a considerable amount of moisture. These beds were called by Dr. Rogers and myself the "Kentani Beds" in the report referred to above, and they were taken to be an

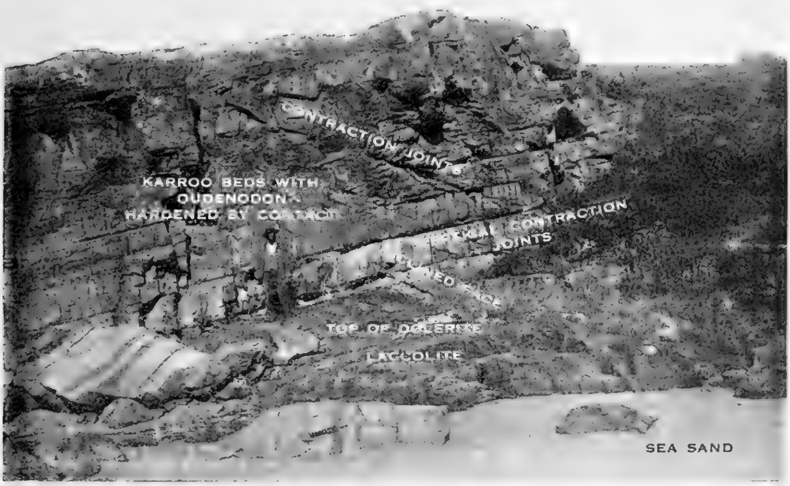

FIG. 6.—Top of laccolite, Mazeppa Bay, Kentani (just west of where the diorite dykes of the Transkei Gap run out to sea at the Koghe River mouth). The bleaching and hardening of the strata are well shown in the fallen blocks, where the bedding planes have become obliterated.

eastern facies of the Beaufort Beds. Dr. Rogers and myself obtained *Oudenodon* remains on the coast of Kentani, and there is an undescribed *Dicynodon* skull from Umtata in the Albany Museum belonging to the same horizon. The specimen was collected by Mr. E. J. Dunn; I submitted it to Mr. Watson, who informed me that the species was of the type found in the lower Beaufort Beds. On the Umkomazan River in Natal Dr. Broom[1]

[1] R. Broom, "Fossil Reptilian Remains from Natal," *Third Report Geological Survey of Natal and Zululand*, London, 1907.

described *Lystrosaurus*, which occurs on a higher horizon, but still within the Beaufort Series proper, so that these beds must occur in a strip running more or less north from East London, where again reptiles of the same horizon occur; but their development is not continuous. In Umsikaba (Flagstaff), in Eastern Pondoland, Dr. Rogers and myself found the Umsikaba Beds (the local facies of the Ecca Beds) directly followed by the Idutywa Beds. At the time, not knowing that the Kentani Beds wedged out, we placed the Idutywa Beds below the *Dicynodon* or Kentani Beds, thinking that they represented the *Pareiasaurus*—zone of the Beaufort Series; this was a natural mistake when working upward in the series, as there is a complete conformity between the Dwyka and Umsikaba (Ecca) Series and the Umsikaba and Idutywa Series. Later, however, working downward, we found the Molteno Beds of the Stormberg System lying directly on the Idutywa Beds.

Western Karroo	Eastern Districts	Pondoland	Transvaal
Idutywa Series	Idutywa Series	Idutywa Series	High Veld Series (Coal Measure Series)
Beaufort Series	Kentani Series	Wanting or only locally developed	Wanting
Ecca Series	Ecca Series	Umsikaba Series	Wanting
Dwyka Series	Dwyka Series	Dwyka Series	Dwyka Series.

PER SALTEM CONFORMITY

Such a conformity as that represented by the Umsikaba Series being followed by the Idutywa Series I will call a *per saltem* conformity. It is due to want of supply of sediment during some lengthened period. The most conspicuous example of it that we have in South Africa is the conformity between the Bokkeveld Series (lowermost Devonian) and the Witteberg Series (Lower Carboniferous), the whole of the Upper and Middle and most of the Lower Devonian being unrepresented. On the supposition that the fossils in South Africa have the same value as time markers as those in the northern hemisphere—which is a debatable point, but one which seems to become more definite as the material accumulates and the study of it advances—this conformity between the Witteberg and Bokkeveld Series is explained by the shore retreating

till detritus from land could no longer reach the particular locality; at the same time, owing to the violence of the currents or the coldness of the sea or for some other cause, the calcareous deposits in the deep ocean did not form, or, if they did form, were dissolved. Then when the sea-floor rose again and the shore advanced, sedimentation began once more, and the new deposits were laid down conformably on the older ones, although a considerable lapse of time had occurred between the two.[1] In the *per saltem* conformity between the Umsikaba and Idutywa Series we have other considerations to take into account. We are dealing with fresh-water deposits. In the Cape Colony proper, that is to say, in the central, south and west portions of the Great Gondwanaland Lake—Lake Union we might call it, as it embraced all the colonies united in the Union of South Africa, whereas the Karroo sediments of Rhodesia and farther north appear to have been deposited under independent sheets of water—the depth was greater and the sedimentation more extensive in the early Karroo times. This portion then filled up and the depression shifted up to the north and east. The hinge of the movement, if we can conceive the lake floors in the two periods as forming two planes meeting along a straight line, would run through Umsikaba (Flagstaff) in Pondoland and the deposits of the earlier depression would then be restricted to irregular arms and bays of the older lake and would form discontinuous pockets, as indeed they appear to do.

THE RELATIONSHIP OF THE DOLERITE TO THE SEDIMENTARY BEDS

It has been necessary to go into a little detail with regard to the sedimentary beds around the great Quizzyhota laccolite, because I seek to prove in the sequel that the dolerites are in part the product of the melting and absorption of the sedimentary beds. I have for many years been looking for a good example to work on, but there have been objections to all of them. The ordinary dykes of the Karroo are of no use, as it is impossible to prove that the space occupied by the igneous rock has been melted out by the dolerite. Immense laccolites occur in the center of the Karroo

[1] E. H. L. Schwarz, "South African Palaeozoic Fossils," *Records Albany Museum*, Vol. I, Grahamstown (1906), 360.

dolerite area in Fraserburg, and one of them furnishes an illustration appearing in Dr. Rogers' *Geology of Cape Colony*,[1] but the contacts are covered. In Burghersdorp, Cradock, and in Cathcart, at Turnstream, along the Great Kei River, there are admirable examples, but only the tops of the great domes appear and no estimate as to the size or shape can be arrived at. A very fine one occurs on the Kentani coast,[2] also exposed only along the extreme top, while the enormous ones of Mount Ayliff, Mount Currie, and others on the Drakensburg Plateau occur in the Molteno Beds and are doubtfully to be ascribed to the same system as the Karroo dolerites. The Quizzyhota laccolite, out of all I have seen in seventeen years' traveling in South Africa, is the best for the purpose I have in hand.

Wherever one finds Karroo sediments, especially those above the *Pareiasaurus* zone, there is usually intrusive dolerite. Again, where the Karroo sediments have been peeled off and the underlying Archaean or Cape system floor is exhibited, there are exceedingly few dykes and those that exist are puny, insignificant stringers as compared to the massive dykes and sills of the Karroo Beds which once lay above them. There is a good example of this to the east and west of Prieska. On the east a loop of the Orange River incloses a peninsula of Karroo shales with a great sill of dolerite. On the west the Griquatown (Pretoria) Beds form the Doornberg Hills, through which runs Prieska's Poort and Keikam's Poort. In both of these gorges thin, nearly vertical, dykes occur, but the main portion of the range is quite devoid of dolerite; yet, looking, to the south where the escarpment of the Karroo Beds begins practically a third of the height of the hills is occupied by dolerite. The occurrence of the dolerite-containing Karroo sediments to the west and south of the Doornberg proves that they were once continuous over the hills.

The question remains: Where did the dolerite come from if there are such feeble channels of supply in the older rocks? Did the Karroo sediments spontaneously melt? I shall seek to prove

[1] 1st ed., 279; 2d ed., 286.

[2] E. H. L. Schwarz, "Origin of the Rand Bankets," *Journal Assoc. for Advancement of Science, S. Africa*, VIII (Cape Town, 1912).

in the sequel that a considerable proportion of the Karroo dolerite is composed of the melted-up sediments, and that the accession of fresh molten material from the deeper portions of the crust was comparatively small in proportion to the amount exhibited on the surface.

THE GREAT KARROO LACCOLITE

All the dolerites of the Karroo—the sills and dykes of the main portion and the laccolites on the east—belong to one and the same system; they together form one immense laccolite of the type known as the "Cedar tree laccolite." The type was first described by Holmes on the La Plata Mountains of Colorado[1] and has since been noted in the gabbro of the Cuillin Hills of Skye,[2] but nothing like the stupendous nature of the Karroo laccolite occurs in other parts of the world. The Karroo laccolite is some 700 miles long by at least 200 miles broad; the great Transvaal laccolite, large as it is, is only 250 miles long. The dolerite sills form generally in the upper portions of the great laccolite, whereas the lumps and expansions forming the subsidiary laccolites, of which the Quizzyhota is one, occur either along the central axis or in the lower portion. In Komgha one is, as it were, in the cellars of the giant structure; the upper stories can be seen to the north in the long table-topped hills of Cathcart. Thence to the north the sills follow each other in countless steps up to the main watershed of the country, which, for a great distance in the west, is a steep escarpment facing south, and generally some 6,000 feet above sea-level, though exceptional heights occur on the north of the Graaff Reinet Division in Compass Berg, 8,500 feet, and Middle Mount, 6,263 feet. East of Compass Berg the main watershed and the central axis of the great laccolite continue in the same direction, but the escarpment curves to the southwest. All these sills dip slightly inward to the north; they are connected by innumerable dykes and often branch and undulate in many remarkable ways. North of the main watershed all the drainage flows into the Orange River, which is held up by the bar across its lower course at the

[1] *Ninth Ann. Rept. U.S. Survey Territories*, Washington, 1877, XLV, Fig. 2.

[2] A. Harker, *Nat. Hist. Igneous Rocks*, 67; "Tertiary Igneous Rocks of Skye," *Mem. Geol. Survey of Glasgow*, Fig. 16, p. 89.

Aughrabies Falls, a little under 2,000 feet above sea-level, and the "kopje veld" of the country south of the main watershed is replaced by wide open flats and the gorges of the rivers by winding, shallow streams of low gradient. Here all the sills dip southward till the old shore line of the Karroo Lake is reached and the older basement

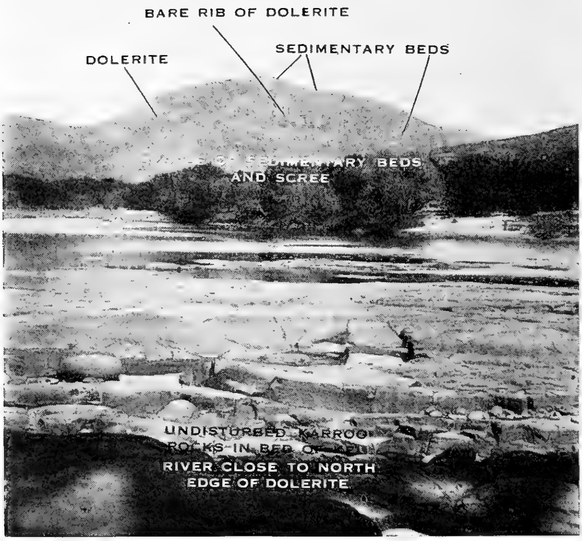

FIG. 7.—Western end of Quizzyhota laccolite, showing dolerite passing into the Karroo rocks of the Krantzes.

of the Karroo makes its appearance. Besides the main watershed there is another topographical feature to be observed: it is the main escarpment of the Karroo sediments and the dolerite sills which coincide with the main watershed in the west, but diverge from it east of Compass Berg. The escarpment begins on the east

with the Amatolas in King Williamstown Division, thence westward is continued north of Fort Beaufort as the Great Winterberg (highest point 7,800 feet), thence to the Sneeuw Bergen (Compass Berg, 8,500 feet), Koudeveld Bergen, Nieuweveld Bergen (Bulthouders Bank near Beaufort West, 6,270 feet), and finally turns round and faces southwest in the Roggeveld Mountains. Although this great ledge, capped throughout with dolerite, forms the main structural feature in the south of the colony, the rivers take no notice of it east of Compass Berg. The Fish River, especially, starts from the main watershed, although this is situated at a much lower level, and cuts great gorges in the country till it escapes to the lower country beyond the ledge. The main watershed coincides with the escarpment from the Nieuweveld to the Compass Berg; thence the escarpment proceeds in an east-northeasterly direction, whereas the watershed runs northeast by east to Delagoa Bay. The watershed is a consequence of the mode of deposition of the Karroo sediments; when these at last rose above the water-level the thickest deposit was highest and from this insignificant crest the rivers began to run over the featureless plain. The ledge or escarpment, on the other hand, is connected with the folding of the Cape Coastal Mountains, probably in a causal connection, that is to say, the dolerite caused the folding; at any rate the southern edge of the Great Karroo laccolite is parallel to the strike of the coastal mountains. The interval between the escarpment and the folded mountains is from fifty to a hundred miles, but the sills advance considerably in front of the escarpment. Thus, on the extreme east, there are the Amatolas, with the laccolite of Debe Nek in front of it, and dolerite dykes extending to points within 4 miles of the Keiskama River, a distance of 50 miles from the crest of the Amatolas, while the folded mountains lie another 50 miles to the south. However, we must regard the great ledge or escarpment as the main boundary of the laccolite and this runs in a gentle arc, with the ends east and west of each other. The center of the bend corresponds to the alteration of the strike of the Cape folded mountains from east and west, to east-southeast, which alteration occurs in Willowmore, Uniondale and Knysna.

The Karroo Beds south of the folded mountains—at least the

remnants left in the Worcester and Robertson Divisions—are not intruded by dolerite.

The great system of sills and dykes runs out to sea with the Karroo rocks near East London and comes in again with them near St. Johns. From the last place the margin runs north to Pietermaritzburg and Ladysmith, thence across the north of the Orange Free State down the Vaal River to Hope Town, Prieska and Brand Vley, thence through Calvinia to near Karroo Poort in the Ceres Division and from there to Beaufort West.

The Stormberg lavas have nothing to do with the Karroo dolerites which the volcanic chimneys pierce. Dolerite dykes indistinguishable in composition from the Karroo dolerites traverse in turn the lavas of the Drakensburg, but these latter are rather to be regarded as dykes connected with the intrusion of the lava.

The dolerite as a whole is an augite-olivine-plagioclase rock; the varieties with a little quartz in granophyric intergrowth or with mica are quite insignificant. One peculiar glassy dyke with nepheline I obtained in Beaufort West,[1] but otherwise the normal dolerite is of an intensely conservative nature. A diorite often traverses the rocks in the east at Cradock and in Komgha and Kentani.[2] These I shall have to refer to later; they are usually taken to be later injections from a primitive magma which has rid itself of the more basic substances, but I shall endeavor to prove that they are the channels down which the more acid materials absorbed by the dolerite from the country rocks are passed out.

THE PROBLEM OF THE DOLERITE INTRUSIONS

Having now established the relationship of the Quizzyhota laccolite to the dolerites of the Karroo and that of the sedimentary rocks to those forming the main portion of the Karroo, we have to inquire how a great mass of igneous rock can have come to lie within the sedimentary rocks without disturbing their stratification and without notably altering them by thermal metamorphism.

[1] E. H. L. Schwarz, "Geological Survey of the Beaufort West District," *Ann. Rept. Geol. Comm., 1896*, Cape Town (1897), 18.

[2] A. W. Rogers and E. H. L. Schwarz, "General Survey of the Rocks of the Southern Transkei," *Ann. Rept. Geol. Comm., 1901*, Cape Town, 1902; "The Transkei Gap," *Trans. Phil. Soc. S. Africa*, XIV, Cape Town, 1903.

The arguments employed here rely on the theory that igneous magmas are solutions not necessarily at very high temperatures. I shall endeavor to establish the fact that such magmas—which in their injection state may be entirely fluid or may consist more or less of crystals already formed, but yet, as a whole, plastic under pressure with the help of solvent water—have certain properties which cause them to crystallize in one standard type with structure and composition constant, no matter what amount of extraneous rock they may have absorbed. I shall apply to a rock magma and the resulting igneous rock the laws which govern the development of single crystals, such as andalusite, in among rocks of totally different composition, assuming that what holds good for individual crystals, also applies to collections of crystals such as igneous rocks are.

The argument will be, in short, that the original molten or fluid magma works its way up into the rocks near the surface of the earth; the release of pressure sets free a certain equivalent of heat, or more probably chemical activity, which is employed in absorbing the rocks encountered. As portions of the country rock become digested, the bulk of the igneous rock at any one time preponderates over the including fragments, and the mineral composition of the magma asserts itself in that it takes from the fragments it is absorbing such substances as are suitable to the formation of the rock of the type represented by the magma, and unsuitable material is passed downward along the supply dykes. Dykes consolidated before the waste material has been removed are represented in the dolerite dykes of the Rainy Lake region in Canada; for instance, the White-Fish Bay dyke, where the outside is a fine-grained dolerite with 47.8 per cent silica, while the inner side is a quartz hornblende rock with 52.5 per cent silica. These dykes are very wide, 120 to 150 feet. In smaller dykes the up-and-down current appears to have been too rapid for the consolidation to catch the two before the completion of the process. Nevertheless, the composite dykes of Arran are of the same nature, although of different origin. The evidence for this argument afforded by the Quizzyhota laccolite will be given in the sequel; it is necessary first to outline the evidence afforded by the development of single crystals such as anda-

lusite and to show how closely the phenomena exhibited by the larger masses, the igneous dykes and laccolites, are presented by the individual crystals.

THE DEVELOPMENT OF ANDALUSITE CRYSTALS

The development of crystals of andalusite, chiastolite, cordierite, and staurolite is most beautifully illustrated in the rocks round the Great Transvaal laccolite. The metamorphic rocks have been described by Hall[1] and I am greatly indebted to him for supplying me with material for study from this locality. The andalusite substance in the less advanced types settles as irregular patches in the shales, schists, sandstones, or whatever type of sedimentary rock is becoming metamorphosed. The minerals of the original rock are, as it were, pushed aside to make way for the introduction of the new material and no absorption is at first apparent. In more advanced types the minerals of the original rock are seen to be whittled away; usually there is an outer zone where the andalusite crystal is more or less free from inclusions. The developing crystals all tend to form in about the same dimensions in the particular rock-type and it is a constant feature that the prism zone early asserts itself, the planes bounding the long axis of the crystal being quite sharp, whereas the basal planes are indefinite, at any rate in the Transvaal specimens that I have seen and in those described by Hall. The Transvaal andalusites apparently do not go beyond this stage, but the smaller variety of the substance, chiastolite, does form very definite, sharply bounded crystals. The section illustrated by Hall (*Survey Report*, Part I, Fig. 1) shows the developing chiastolite with the center still full of inclusions, the outer rim clear, and the complete crystals in which all but a small string of inclusions in the center has been cleared away.

For the later stages of the development of andalusite I will take the andalusite schist of George.[2] The occurrence is on the Zwart

[1] A. L. Hall, "The Geology of the Haenertsburg Gold Fields," *Report Geol. Survey, 1907*, Pretoria (1908), 43 ff.; "Contact Metamorphism in the Western Transvaal," *Trans. Geol. Soc. S. Africa*, Vol. XII, Johannesburg (1910), 119.

[2] E. H. L. Schwarz, "The Andalusite Schist of George," *Albany Mus. Records*, II, 164 (1907), Grahamstown.

River along the main road from George to Knysna, about 5 miles from the former place; there is a small granite dyke exposed on the road section piercing the mica schists belonging to the Malmesbury Formation; about 5 yards from the granite the rock suddenly becomes full of well-formed andalusite crystals about an inch in length. The crystals are coated with scales of mica and usually have drawn out extremities in which mica flakes and andalusite substance have not yet become separated; some crystals, however, are sharply terminated. At the actual contact there is a thin zone of Cornubianite, never more than an eighth of an inch in width, in which there are small crystals of andalusite averaging .7 mm. in length and .15 mm. in breadth. Eye-shaped patches of the same substance occur where the schist has been kinked, and both crystals and "eyes" contain pellucid egg-shaped grains of quartz and a little red-brown mica, all that is left of the original sand grains and mica-flakes of the original rock. Occasionally a mica-flake of the schists ends abruptly at the margin of the andalusite, and in the latter there is the continuation of the flake rounded off in the usual manner of these inclusions; the flake has the appearance of having had its end melted and a portion incorporated in the new crystal of andalusite. When the crystals of andalusite have sharp ends, the dome faces are not equally developed on either side of the end; they follow the sides of the original kink of the shale in which the substance has been deposited, as if the crystal were monoclinic—another instance of the feebleness of the crystallizing force in the terminations as compared with the sides.

The larger crystals may be divided into the perfect forms and the irregular ones. In a longitudinal section of the former the substance of the andalusite is transparent with the usual pleochroism. Trains of rounded black dots and stout, short rods of rutile follow more or less the direction of the planes of parting. The black dots are graphite showing in reflected light an adamantine luster with white faces; they are probably carbonaceous matter that has aggregated in the andalusite substance from the flocculent material in the schists. The rutile needles also appear to have been enlarged from the minute ones in the biotite flakes. Rounded flecks of red-brown mica occur throughout the substance as well as the egg-

shaped pellucid quartz grains; these are the remnants of the minerals of the schists digested and almost absorbed. In the irregular crystals trains of unaltered mica-flakes pass right across the prisms, but in the perfect crystals these "segregation bands," as they would be called in igneous rocks, have been broken up and digested in the main. In many sections, however, little rounded specks occur which, under the microscope, appear as little xenoliths of the country rock. The andalusite, unable to penetrate and rid itself of these remnants, has tied up the indigestible substance in little rounded pockets, which may be as much as 1 mm. in diameter.

The andalusite substance apparently came from the granite, because it occupies spaces originally taken up by minerals of varying composition; some of the substance of the matrix has undoubtedly contributed to the building up of the andalusite crystals, but the part represented by the potash, iron, and magnesium of the biotite and by the potash of the muscovite must have been replaced by new material. There is further reason for believing that the new substance came from the granite, because in Stellenbosch, under precisely similar conditions, large feldspar crystals develop. Now the granite at George is a muscovite granite and would want all the potash for its own minerals, and therefore passed out aluminium silicate, but the Stellenbosch granite is a biotite granite and therefore could spare the potash, hence it passed out potash aluminium silicate.

THE ACID RESIDUE AFTER ABSORPTION

It will be evident from an inspection of the photographs accompanying this paper that the sediments have been dissolved by the dolerite, and from the analyses given it is apparent that the siliceous residue has been removed. Where has it gone to? As there are only channels of communication downward, the answer is that the siliceous material has gone toward the deeper portions of the earth's crust and there solidified. The granite bosses of the western province of Cape Colony represents the siliceous residues; they originally had Karroo sediments above them, probably with dolerite intrusions. In the Cape Town granite there are dolerite dykes associated with the granite, which go right up through the Table

Mountain sandstone.[1] I do not, however, wish to include in this discussion the question of the granite bosses as I have no new studies on them to offer, but the evidence for the absorption of sediments is very plain, especially along the granite contact at Sea Point, which was used by Hutton in illustration of his principles, and at Robertson, where the granite is bordered by a rim of *lit-par-lit* injection and other phenomena that I believe will afford positive evidence for the part these masses played in the general igneous injection of the country, when the material is worked up.

The igneous rocks of Cape Colony are very simple—enormous tracts of dolerite above and granite below; there are none of the complicated varieties to obscure the main principles. There is a curious side-issue in respect to the injection of andalusite crystals or occasionally orthoclase crystals in the sediments round the granite.[2] I assume for the purpose that the evidence for the absorption of sediments by the granite is as complete as for the dolerite, at least in Cape Colony, and that the original magma plus the material absorbed separated into dolerite and granite. We do not at present know what the proportions of basic and acid rock were, but we can suppose that they were equal. If, now, we take the mean of any analyses of normal granite and dolerite and contrast it with the analysis of any non-calcareous slate, adding a little sandstone if the silica percentage is small, we shall find that the excess of material after the igneous rock has used up all it wanted, consists of silica, alumina, and potash, and naturally, if the igneous rock is locally rich in potash, then of silica and alumina only. That is to say, the very general injection of silicate of alumina in the form of andalusite, chiastolite, and sillimanite, and the fairly common injection of orthoclase crystals, would be a result of the absorption of the slates and the rejection by the granite-dolerite magma of waste material. I take as an illustration the analyses given in Professor Judd's *Students' Lyell*, which can easily be checked. A more suitable series of analyses would be the slates intruded by the granite, the granite and the dolerite dykes in the granite, which

[1] See F. H. Hatch and G. S. Corstorphine, *Geology of S. Africa*, Figs. 2 and 3; pp. 37 and 41.

[2] E. H. L. Schwarz, *Ann. Rept. Geol. Comm., 1897*, Cape Town (1899), 54.

occur on the Wynberg side of Table Mountain, but I have not the material before me; a large number of similar series of analyses that I have tried give the same result.

	Granite	Dolerite	Mean	Mica-Schist	Excess after Absorption
S_1O_2	76.1	50.2	63.1	66.2	3.1
Al_2O_3	13.4	15.0	14.2	18.6	4.4
$FeO_1Fe_2O_3$	1.3	16.9	9.1	5.3	...
MgO	.2	5.8	3	1.2	...
CaO	.3	10.5	5.4	.4	...
Na_2O	3.1	2.2	2.6	2.2	...
K_2O	4.9	1.4	3.1	3.9	.8

THE RESEMBLANCES BETWEEN THE DEVELOPMENT OF ANDALUSITE CRYSTALS AND IGNEOUS INJECTION

In the case of the George andalusite we have a crystal substance injected into a rock. It first occupies cavities ready made for it, then with accession of further material, it dissolves, or as we should say in speaking of igneous rocks, melts up portions of the invaded rock, assimilates suitable substances and passes out the residue. Segregation bands develop where conditions are unfavorable, and included blocks or xenoliths entirely unaltered or more or less "metamorphosed" occur. All the phenomena of igneous injection are portrayed without the aid of any great heat, though hot water circulating under pressure was no doubt the agent by which the transference of material was accomplished. In the constancy of size also the masses of igneous rocks are simulated. The Zwart River crystals are about an inch in length—4 cm. perhaps would be the best average. None are much smaller or larger. A little farther on a similar but less perfect development of crystals occurs where the size is half that of those of the Zwart River material, and again in the chiastolite slates of the Transvaal a much smaller average is attained. So throughout the Karroo the dykes and sills are very constant in thickness; the laccolites of the Drakensberg Plateau and the granite bosses of the southwest are of approximately equal bulk. The granite masses of Cornwall and Devon are another striking example. It would seem that as with crystals so with magmas, there is a limit of size.

THE CHANNELS BY WHICH THE ACID RESIDUES ESCAPED

The escape of siliceous material from the dolerites should leave somewhere some trace. As the channels of supply function at the same time as conduits for the waste material, there should exist occasionally composite dykes of the type described from Canada by Lawson,[1] and from Norway by Vogt,[2] which have basic margins and granite or syenite centers. Similar ones occur in Arran consisting of selvages of augite-andesite and centers of quartz-felsite as described by Judd.[3] They have also been found in Skye and the Thüringer Wald.[4] No dykes of this nature have so far been noticed in South Africa, but diorite dykes genetically related to the dolerite sills are fairly common about Cradock and Kentani. A pair of parallel dykes in the Transkei were described by Dr. Rogers and myself in 1901; they run a little north of the Quizzyhota, cross the Kei, and traverse the Kentani district to its eastern border along the Kogha River; the easy weathering of this rock as compared to that of the dolerite and Karroo sediments has left deep furrows in the land, which have been given the local name of the "Transkei Gap."[5] Another diorite mass occurs at Gonubie along the main road from Kei Road to Komgha. The Gap-rock was described by Dr. Rogers in the paper referred to, and I reproduce it for comparison with the description of the dolerite of the Quizzyhota.

The rock forming the dykes of the Gap is a peculiar one, differing in important respects from any intrusions hitherto found by us in the Karroo Formation, although as will be pointed out in the following notes, it has a distinct relationship to the olivine-dolerite of the sheets.[6] It consists chiefly of the following minerals in the order of their usual relative abundance: plagio-

[1] A. C. Lawson, *Report on the Geology of Rainy Lake Region, Geol. and Nat. Hist. Survey, Canada* (Ann. Rept., 1887–88), Part F.

[2] J. H. L. Vogt, *Geol. Mag.* (1892), 82; W. C. Brogger, *Eruptivgesteine des Kristianiagebietes*, I (1894), 56.

[3] J. W. Judd, "Composite Dykes in Arran," *Q.J.G.S.*, XLIX, 545 ff.

[4] A. Harker, *Tertiary Igneous Rocks of Skye*, chap. xii.

[5] A. W. Rogers and E. H. L. Schwarz, "The Transkei Gap," *Trans. Phil. Soc., S. Africa*, XIV. (Cape Town, 1901), 63.

[6] The olivine-dolerite which forms the intrusive sheets of the Transkei is very like the rocks occurring in the same manner near Beaufort West, and described by E. Cohen, *Neues Jahrb.* (1874), 195.

clase, hornblende, augite, quartz, red-brown mica, orthoclase, apatite iron ores, sphene and decomposition products such as chlorite, uralite and calcite. Variations in the proportions of these minerals show that the rock differs considerably in composition from point to point.

The plagioclase has almost always a zonal structure; . . . . it frequently shows crystal outlines when in contact with the hornblende and augite, sometimes small crystals of the feldspar are entirely inclosed by the hornblende and augite. This ophitic structure though found without difficulty in all slices of the rock examined, is not nearly so pronounced a feature as in the olivine-dolerite.

The original hornblende is mostly of a pale greenish-brown colour, with feeble pleochroism, but a bright green strongly pleochroic variety also occurs, sometimes forming part of a crystal which is mostly made up of the pale kind. Occassionally small crystals showing the prism faces are met with, but the larger plates seen in the slices are always irregularly bounded by contact with other minerals, notably plagioclase. The last remark applies also to the augite, which is colourless in section and appears to be identical in character with the augite of the olivine-dolerite. The hornblende and augite usually occur together, intergrown with their orthopinacoidal faces parallel. The augite often forms the inner part of a section of the two minerals; outside this area the hornblende encloses the whole. The structure is easily seen by ordinary light under the microscope, as the augite is colourless and the hornblende pale greenish-brown, but between crossed incols the minerals are still more clearly seen owing to their extinguishing in different positions of the nicols. The intergrowths of the two minerals are sometimes twined, the composition plane being the ortho-pinacoid, common to both minerals.

Hornblende is rarely found in the olivine-dolerites but it does occur in them, *e.g.*, in the coarse olivine-dolerites of the sheet seen on the shore between the Gxacha and Kologha Rivers (Kentani) and in the Kologha sill. In a slice from the dolerite sill exposed along the Kei River at Mimosa Hill (the Kologha sill) there is much hornblende of the same variety as that in the Gap-rock and it is also intergrown with augite.

The mica is a red, strongly pleochroic variety, frequently altered to a very pale, greenish mineral with weak double refraction. It frequently encloses small zircons round which there is always a pleochroic halo; zircon occurs similarly in the hornblende. This mica occurs frequently and is a most important constituent of the Gap dykes; a precisely similar variety is found in almost all slices of the Transkeian olivine-dolerites but in very small quantity.

Quartz is abundant in some parts of the Gap dykes and present in all slides examined. It was the latest constituent to crystallise out from the liquid magma; it frequently forms a micropegmatitic intergrowth with a cloudy untwined feldspar which is probably orthoclase. Both micropegmatite and quartz are occasionally seen in the slices of the dolerites, but they are generally very subordinate constituents of the rock.

The iron-ores are magnetite, ilmenite with which sphene is often associated and iron pyrites. Apatite is always present, sometimes in considerable quantity.

The rock forming the dykes of the Gap may be called quartz-mica-augite diorite; it differs from the olivine-dolerite very considerably in the absence of olivine and in the presence of large amounts of hornblende, brown mica and quartz as well as the more acid varieties of plagioclase. It is very noticeable, however, that none of the minerals which characterise the Gap-rock are foreign to the olivine-dolerites and in the case of the Kologha sill the dolerite in parts approaches the Gap-rock in character rather closely by the increase in the amount of hornblende, red mica and the zoning of the plagioclase. The affinity between the two rocks is sufficient to make it preferable to regard the Gap-rock as derived from the magma which supplied the dolerite intrusions rather than the result of a quite different order of events. If we consider the Gap-rock as a late product of the magma after the dolerite had been got rid of, our view will explain the facts observed under the microscope and in the field; for while the evidence of a microscopic examination shows that the Gap-rock and the dolerite are genetically related, the field evidence conclusively proves that the latter rock had solidified before the former was intruded through it.

I do not think the last-mentioned fact invalidates the present view that these diorite dykes are the channels of escape of waste siliceous material as well as supply dykes of basic material. The dolerite spreads upward and the conduits of the upper sills must have remained open after the consolidation of the lower sills. There has been noted also a sequence in the infillings of the composite dykes of Arran and Skye. It may be noted that in the latter locality, where the granite invades the gabbro, it often partially fuses it and converts it into a rock consisting of hornblende and feldspar (labradorite to oligoclase).[1] At any rate the absorption of the sediments by the dolerite necessitates the escape of siliceous material, and the diorite dykes, where the differentiation into an acid and basic series has not been completed, are of the necessary constitution. The fact that the diorite dykes have been noticed where there is great development of laccolites, as at Cradock and in Komgha, is of special importance. The ordinary sills of the Karroo have been intruded for miles along inclined planes and, as the thickness of the dykes and sills varies very little, the diffusion of the acid and basic parts of the magma would have been unrestrained. In the laccolities, however, which form great lumps with

[1] A. Harker, *Tertiary Igneous Rocks of Skye*, 171.

comparatively narrow supply dykes, the channels of supply and escape of waste siliceous material are so small that the diffusion of the substances in the magma would have been hindered and as a result these dykes consolidated with rocks of the average composition.

THE DIFFUSION DUMBBELL

Taking the whole evidence which the granite bosses, the diorite dykes and the dolerite laccolites afford us in Cape Colony, one is led to conceive of a system of igneous injections of a dumbbell shape. Below we have the Malmesbury clayslates, above the Karroo sediments, in between the various siliceous sediments of the Cape system, or sometimes in the north of the Pal-Afric group Kheis quartzites and Pretoria iron-bearing quartzites. Below, the magma eats out great holes and fills them with granite; above, the same magma eats out the holes and fills them with basic rock. In between are thin dykes of communication usually dolerite but uuder certain conditions diorite. The slates above and below became absorbed and the material from both was added to the general stock of magma. The average magma remained fluid in this dumbbell system for some time, till for some reason the acid part concentrated in the lower part and the basic in the upper part, the diffusion taking place through the narrow part of the dumbbell and sometimes the average magma became caught in this part and became consolidated as diorite.

The facts are plain enough and it is perhaps as well to content oneself with them at present, but there is an explanation which, if only speculative, may be worth mentioning in order to show that this differentiation of an average magma is not wholly unexpected.

THE IONIC SEPARATION OF SUBSTANCES IN A ROCK-MAGMA

When an iron-bearing rock weathers at the surface of the earth, the iron does not travel outward to the sea along with the soda, lime, and potash but seeks the center of the earth.[1] The fact is easily recognizable in the replacement of limestone by iron ores,

[1] E. H. L. Schwarz, *Causal Geology* (1910), 73; "Selective Absorption of Substances in the Earth's Crust," *Journal Assoc. for Advancement of Science, S. Africa* (Cape Town, 1912), 181.

which are of common occurrence; in these cases certain conditions have caused precipitation of the iron from solution, but where the conditions are not favorable, the iron goes on its journey downward toward the base of the crust. Weak solutions such as these which carry the iron are ionized and the metallic ion carries a positive charge of electricity; the metallic ion possibly is attracted by the magnetic core of the earth, but however that may be, the iron goes down and must come to rest in the base of the crust beyond which water cannot penetrate. This would lead to an accumulation of a positive charge at the base of the crust. Above this is suspended a solution or a fluid magma which is an electrolyte,[1] that is, one in which the substances are ionized and the metallic ions carry a positive charge and the acid ions a negative one. Under such circumstances the negative, acid ions would be attracted by the positive charge at the base of the crust and the metallic, positive ions would be repelled, and in that way a magma of average composition would be differentiated into an acid and basic series, the acid part accumulating in the lower half of the dumbbell and the basic in the upper. Whether this cause is sufficient for the effect I do not know, but considering the immense time during which geological phenomena take place, a small but persistent electrical attraction and repulsion, such as exists under the circumstances, would have far-reaching effects.

[1] C. Barus and J. P. Iddings, *Amer. Jour. Sci.*, XLIV, 242.

AN ACCESSORY LENS FOR OBSERVING INTERFERENCE FIGURES OF SMALL MINERAL GRAINS

ALBERT JOHANNSEN
University of Chicago

As long ago as 1880 Bertrand[1] discovered that in the bubbles which are found so frequently in the Canada balsam between the mineral section and the cover-glass, there may be seen an interference figure of the mineral lying below it. The bubble acts as a lens of short focal length and takes the place of the objective, while the ocular and objective combined act as do the Bertrand lens and the ocular in the usual method of observing interference figures.

Later, Schroeder van der Kolk[2] carried this method a step farther. He placed a drop of glycerine upon the cover-glass of the slide to be examined and stirred it rapidly with a thin rod so that it became filled with small bubbles. Over this he placed a cover-glass and, between crossed nicols and with a medium-power objective, he depressed the tube a very little below the focal plane and found in each bubble a small interference figure. To avoid the necessity each time of preparing anew a glycerine foam, Schroeder van der Kolk used the following simple device: He placed a drop of Canada balsam on an object-glass and, if necessary, cooked it. After producing foam by rapid stirring, he placed a cover-glass upon it and the instrument was completed. To use it he placed it, cover-glass downward, upon the rock section and shoved it into such positions that bubbles appeared over the desired spots.

In using this method, the present writer found that he could not produce bubbles in well-cooked balsam. If undercooked, the gum would squeeze out at the sides and stick to the rock slice under examination and the bubbles would become distorted from their

[1] E. Bertrand, "De l'application du microscope à l'étude de la minéralogie," *Bull. soc. min. France*, III (1880), 93–96.

[2] J. L. C. Schroeder van der Kolk, "Ueber eine Methode zur Beobachtung der optischen Interferenzerscheinungen im convergenten polarisirten Lichte, insbesondere in Gesteinsschliffen," *Zeitschr. f. wiss. Mikroskop.*, VIII (1891), 459–61.

spherical form. Another objection is that the extra cover-glass increases the distance between the balsam film and the mineral and, as a consequence, a dark border surrounds each bubble and cuts down, materially, the size of the interference figure. If a piece of glass, full of minute bubbles and of the thickness of a cover-glass, could be prepared, it would be a great improvement. By removing the cover-glass of the rock section to be examined and pressing the new glass down over it on a drop of oil, the interference figures would appear sharp, of the full size of the bubbles, and without a dark border. Having no such glass the writer has prepared small lenses as follows:

A glass rod was heated over a Bunsen burner and was drawn out as thin as possible. Pieces of the glass threads thus obtained were again heated and again drawn out to hair-like thinness. These were broken into lengths of an inch and a half and the extremities held an instant in the edge of the flame, whereby truly spherical globules were produced at each end. After preparing a number of these spherical lenses, they were examined under the microscope and all that were not perfect or which contained bubbles were rejected. Likewise only those which had a diameter of less than $\frac{1}{125}$ of an inch (0.2 mm.) were retained. If, now, such a lens is placed directly in contact with the cover-glass over the mineral to be examined, and the microscope arranged with crossed nicols, ocular, and a medium- or low-power objective (No. 0 to 4, Fuess), there will appear in it a small but perfect interference figure. The microscope should be focused upon the glass sphere and the tube then slightly raised. A condensing lens is not necessary but without it part of the figure is cut off by the dark border. The optical character and dispersion can be determined as well by this method as by the use of a Bertrand lens, and the figure is decidedly sharper. By its means it is possible to examine the interference figures, undisturbed by surrounding minerals, of grains smaller than is possible by the Lasaulx, Klein, or Bertrand methods, and it possesses the further advantage that the mineral and the interference figure can be seen at the same time. By shifting the lens, the optical orientation of all of the grains in a section can be determined. When used in connection with the Fedorow universal

stage, interference figures may be obtained with low power objectives. This extends the usefulness of the Fedorow stage since it increases the rapidity with which determinations may be made in certain cases.

To permit the rapid examination of a slide the writer attaches a bit of soft modeling-wax to one side of the stage and in it places the glass thread at such an angle that the lens globule is in the center of the field and rests against the cover-glass of the mineral section. The latter may now be shifted around the stage as much as is desired, bringing, successively, the different mineral constituents under the lens, which remains undisturbed in the center of the field. Another method is to attach the rod of the lens to the rim of a cork ring, allowing it to project toward the center, and so tilted that it rests on the same plane as the bottom of the ring. This method better protects the delicate glass rod but is not quite so convenient, since both rock section and cork must be moved when it is desired to place different minerals in the center of the field.

Reviews

Geology of the Haliburton and Bancroft Areas, Providence of Ontario. By Frank D. Adams and Alfred E. Barlow. Ottawa: Canada Department of Mines, Memoir No. 6. Pp. 419; 70 photographic illustrations, 7 figures, 2 maps.

The Haliburton and Bancroft areas described by Adams and Barlow are located in the southeastern part of Ontario within the Canadian Protaxis. They constitute a pre-Cambrian complex of about 4,200 square miles, of which the southern portion, the Bancroft area, consists mainly of limestone and dolomite, with minor clastic sediments, intruded by syenites, gabbros, and diorites, and intercalated with acid eruptives, the whole invaded by an enormous batholithic development of granite gneisses and granites, exposed mainly in the Haliburton area to the north, and making up more than half of the total extent of the region. This complex was intricately folded in pre-Cambrian times, mainly under conditions of flow contemporaneously with the intrusion of the granite gneisses and granites, the major axis of deformation being N. 30° E.

Like most of the Protaxis, this region is beveled by a nearly level plane of erosion whose inequalities result from etching and the unevenness of glacial deposition. Here and there monadnocks of igneous rock rise to a height of several hundred feet above their surroundings. To the south, this surface dips under nearly horizontal Paleozoic limestones beveled by a much smoother plain. The fertility and cultivation of the conspicuous, steep-faced outliers of Paleozoic limestones studding the boundary, contrast strikingly with the more sparsely settled, slightly tilted pre-Cambrian, much of which is a succession of low, rolling, barren knobs of rock rising from a bowlder-strewn waste, whose drift and rock depressions are frequently occupied by lakes or swamps. Green, unbroken forests still withhold a portion of it from the desolateness to which it is doomed, a land in which canoe and trail are still necessities of travel. From the Paleozoic front, the undulating plain which bevels the pre-Cambrian rocks rises toward the northeast, with a gradient of about 8 feet per mile, to a wavy line of maximum elevation of about 1,500 feet trending a little south of east through the northern part of the

Haliburton area. From thence it descends toward the northeast, thus dividing the drainage to the south and west into the St. Lawrence system and to the north into the Ottawa River. Both the configuration of the lakes and the direction of the streams is guided to a large extent by the foliation of the rocks. This is especially true of the limestone area while the drainage lines on the granite gneisses show much less dependence on tectonic lines.

The limestones and dolomites of this region are a part of a pre-Cambrian limestone terrane stretching from Georgian Bay to beyond the St. Maurice River in the Province of Quebec. In the contiguous area to the southeast of the Haliburton and Bancroft areas, Logan's Hastings district, these limestones and dolomites, while containing basic intrusives, are less highly altered than in Logan's Original Grenville of Quebec, where they are intruded and intensely altered by the same granite gneisses which invade them in the Haliburton and Bancroft areas. Since the less altered limestones of the Hastings district grade into the highly altered limestones to the northwest without divergence of strike and without the interposition of basal conglomerates, or other evidences of unconformity, Adams and Barlow believe that the entire terrane constitutes one series to which they give the name Grenville, and with this they correlate the limestones of the Adirondacks, thus grouping as one, an areal exposure of 83,000 square miles of limestone, one of the greatest developments of limestones in North America, and the greatest in the pre-Cambrian. The existence of certain conglomerates in the Bancroft area, however, has caused Miller and other geologists to suspend judgment as to the unity of this region.

The position of the Grenville Hastings series in the pre-Cambrian is still left in doubt since they have not been found to connect with any of the correlated units. Nor do they resemble any of them lithologically. In the linear character of their topography and in their great dominance of sediments, they are more like the Algonkian than the Archean. Adams and Barlow class them as Archean, evidently using the term as synonymous with pre-Cambrian.

The basement on which the sediments rest has nowhere been found. Adams and Barlow, however, follow Lawson in their belief that in cases like this, the sediments were deposited on the granites and that later the granite basement became re-fused and intruded into the sediments.

The thickness of the sediments in the Haliburton and Bancroft areas is estimated by the authors to be about 17 miles, though they recognize the probability that isoclinal folding and other factors may

have added to the apparent thickness. One feels rather quizzical at the confidence with which they present this figure.

The least metamorphosed, pure limestones are mostly fine-grained, and of a bluish color, the dark color being due to organic matter. They are interstratified with dolomitic and magnesian beds, but the pure limestones dominate. This great development of pure limestones modifies the prevailing opinion that the pre-Cambrian does not contain many pure limestones.

The magnesium carbonate is found to occur in the mineral dolomite, and as a slight replacement of calcium carbonate in calcite. All gradations are also found, from pure limestones to argillaceous and quartz-bearing limestones and dolomites, quartzites and paragneisses, but the impure rocks are highly recrystallized as a rule. Most of the limestones and dolomites have been intensely metamorphosed, but the relative importance of intrusion and of intense folding in bringing this about is not always clear. The carbonates have adjusted themselves to stress strain conditions by plastic flow, including recrystallization, gliding, shearing, and granulation. In general the limestones were more plastic than the silicate or quartz rocks associated with them, flowing in between the fragments of the latter.

The most apparent effects of metamorphism on the limestones are a coarsening of the grain, and a change of the color from blue to white, and the development of graphite, complex silicates, and heavy oxides. Pyroxenes, amphiboles, feldspar, epidote, quartz, scapolite, magnetite, spinel, and many others are more or less common developments. There is also a notable series of sulphides, among them mispickle, galena, pyrite, molybdenite, orpiment, and realgar. To what extent these new developments represent recrystallization of materials originally present and to what extent infusion of new materials is not clearly determined. Where the limestones have been invaded by basic intrusions and, on a much larger scale, where they have been invaded by the granite gneisses, they have been altered either to a granular aggregate of pyroxenes and hornblende, with scapolite and accessory minerals, or to a feather-like aggregation of hornblende with other silicates and residual calcite and dolomite. To these rocks, approximating the composition of diabase, the name of amphibolites have been given. The granite gneisses are also full of amphibolite inclusions most of which probably represent altered limestones. From a comparison of the composition of three amphibolites, representing different stages of the alteration of limestones by granite gneiss intrusion, the authors conclude that the process of

amphibolitization involves first a loss of carbonates and a development of feldspar and pyroxene in their stead. In the second stage all carbonates are replaced by pyroxene, feldspars, and scapolite, and finally the rock becomes in texture like a fine-grained igneous rock composed of feldspars, hornblende, and pyroxene. Without presenting analyses of the fresh limestones, the authors assume that this change involves loss of lime and carbonic acid from the limestones and transfusion of silica, alumina, iron, and magnesia with some alkali and titanic acid from the granite to the limestones. From the data presented this conclusion is only valid if the change took place without loss of mass. The limestones and dolomites are also altered in many places to serpentine marbles. Microscopic studies show, however, that the change to serpentine is preceded by the development of other silicates such as pyroxenes and amphiboles.

The gabbros and diorites occur either as stock-like masses piercing the limestones and altering them to amphibolite, or as dikes cutting the limestones, and as sheet-like masses whose relation to the limestone is uncertain. Some of the latter may be altered pyroclastics. The dikes and sheets have the character of granular amphibolites.

Relatively small masses of acid volcanic orthophyre with distinct flow structures are intercalated with the limestones.

The nepheline corundum-bearing syenites occur between the granite gneisses and the limestone and with one exception within the limestones, thus seeming to corroborate Daly's hypothesis of the genetic relationship of syenites to limestones. All contain limestone inclusions. Certain phases consist largely of nepheline with few femic constituents, others almost entirely of femic minerals, while in some plagioclase feldspar is the dominant mineral.

The greatest petrographic unit of the area, the granite gneisses, presents three principal phases. About 82 per cent of its area, the red gneisses, is composed mainly of oligoclase, with some potash feldspars, quartz and femic accessories; the remainder of the area consists of gray gneisses, high in femic constituents, and amphibolite inclusions, derived mainly from the metamorphosed invaded limestones. The amphibolite inclusions vary in extent from acres to minute lenses, and present all stages of dissolution. Some are still angular and massive, others are pierced by pegmatitic phases of the granitic magma, while pieces which have flowed many feet from each other are separated by fine-grained gneiss. Clear cases of the solution of the amphibolites in the granites, while uncommon, suggest that some of the gray gneisses may have developed in this way. In general, however, the amphibolite inclusions

have not become gneissose, and were much more brittle than the relatively plastic granite gneisses in which they flowed.

A minor occurrence of very acid gneissic red granite, consisting dominantly of potash feldspar and quartz, was found to contain nodules and small vein-like masses of zonally arranged quartz sillimanite and tourmaline, which are regarded by the authors as acid differentiates and not as inclusions.

The alignment of the granite gneiss batholiths with the major axis of folding, and the parallelism of the foliation and folding of both sediments and intrusions, indicates that the invasion of the granite gneisses and the deformation of the region was largely contemporaneous. Intrusion was effected by the up-bowing of the sediments, and by the invasion of the magma as a pegmatitic facies into the shattered sedimentary border zone, or by *lit-par-lit* intrusion, followed by the stopping-off of the intruded rocks into the magma. Solution of the sediments was a very subordinate process.

The authors believe that the granite gneisses were in a partially crystallized but pasty condition when injected, as shown by their flow lines, the granulation of the feldspars, and the elongation of the more plastic quartz crystals. While most of the deformation of the granite gneisses took place without fracturing, other than the granulation of mineral particles, some of the sharp folds grade into faults, or shear zones which are invariably filled with granite pegmatite. Many of the granite pegmatitic veins in shear zones and in the border zones of the sediments were intruded before deformation was completed, and became granulated and sheared into pseudoconglomerates, while others were injected after deformation was completed and show no fracture or distortion.

The principal exploited economic mineral of these areas is corundum from the syenites. Gold and copper-bearing veins are also known to dissect the amphibolites, while magnetite is found as a segregation in the syenites and in bands in the stratified amphibolites. Apatite and graphite-bearing pegmatites cut the limestones, and graphite also occurs in lenses parallel with the stratification of the limestones. Post-glacial deposits of marl and ochre have been located, and building stones in the form of marble, serpentine marble, and sodalite are described as valuable but as yet undeveloped resources.

This report is rich in illustrative and descriptive information on the mechanics of intrusion, the adjustment of materials to stress strain conditions, magmatic differentiation, and on contact metamorphism. If anything, it may be mildly criticized for too much detail. In order

to get at the essentials, the reader is often obliged to skim over many superfluous details on the optical properties of minerals. Some of the important conclusions may be open to the objection that they are based on insufficient evidence; namely, the great thickness and conformability of the sedimentary series, and the transfusion of certain materials from the granite gneisses to the limestones. EDWARD STEIDTMANN

[*Author's Abstract*]

Production of Graphite in 1911. By EDSON S. BASTIN. Advance chapter from Mineral Resources of the United States, 1911. U.S. Geological Survey.

The natural graphite mined and concentrated in the United States is variable in amount, principally because the process of milling flake graphite, the most abundant type of domestic material, is still in an experimental stage. Because of this unreliability of the domestic supply most of the large consumers of graphite prefer to depend for their supply on imported material.

In 1911 the quantity of graphite imported into the United States for consumption was 20,702 short tons, valued at $1,495,729. In contrast to this the total domestic production was 3,618 short tons of natural graphite, valued at $288,465, and 5,072 short tons of manufactured graphite, valued at $664,000.

The great bulk of the graphite imported into the United States comes from the island of Ceylon, and the United States has for many years been the principal market for this Ceylon product. Considerable amounts of graphite are also imported into the United States from Mexico and within the last few years graphite from Chosen (Korea) has entered the market.

The principal feature of this report as distinguished from previous reports on the production of graphite in the United States is a summary of existing knowledge in regard to the famous graphite deposits of the island of Ceylon. The literature concerning these deposits is widely scattered, mostly in obscure publications. The geological occurrence of the Ceylon graphite, method of working the deposits and of preparing the graphite for the market are discussed, and the various theories which have been advanced to account for their origin are summarized. A list of the principal publications dealing with these deposits is included.

The report also describes a somewhat similar occurrence of graphite near Dillon, Mont., and concludes with a bibliography of all of the important publications dealing with the graphite deposits of the United States.

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THE RELATIVE SOLUBILITIES OF THE CHEMICAL CONSTITUENTS OF ROCKS

C. H. SMYTH, Jr.
Princeton University

Several years ago, while making an estimate of the rate of chemical denudation, which, from skepticism in regard to the trustworthiness of the available data, was never offered for publication, the writer was impressed with the desirability of determining, so far as might be possible, the average relative rates at which the predominant chemical constituents of rocks were taken into solution in drainage waters. So far as could be learned at the time, the problem had never been definitely formulated on a quantitative basis, nor its solution in numerical terms attempted.

The writer's aim was to obtain definite numbers which should express the relative rates at which the common oxides are dissolved by natural waters, using the oxides in the ordinary conventional sense in which they are considered as rock components. To be more explicit, the actual minerals, of which rocks are made up, were not considered at all but merely the ultimate chemical composition of rocks, expressed in terms of oxides. While the method pursued gave results suggesting interesting possibilities, it was felt that, as in the case of the problem of chemical denudation, the data available were not sufficiently trustworthy to warrant publication. At present, however, more reliable data are at hand

and, though still defective in certain respects, they afford the needed basis for a preliminary discussion of the problem.

At the outset, it should be made clear in what sense the term "relative solubilities" is used. Probably, all but the simplest minerals, when acted upon by water, do not merely dissolve, in the strict physical sense of the word, but decompose,[1] so that the constituents appear in the solution in quite different proportions from those in which they are present in the mineral. As rocks are mixtures of minerals, it is obvious that, when they are acted upon by water, there must be a very complex series of decompositions and interactions. With the details of these operations, the present inquiry is not concerned, but merely with their final results as represented by the materials in solution, derived from the rocks. For this purpose, the latter are regarded as composed, not of minerals, but of oxides, as ordinarily expressed in the results of chemical analysis. Such a conception of the rocks requires, of course, no apology, as it is necessary, and universally used, in dealing with them from the chemical point of view.

Thus, by the term relative solubilities, as here used, is meant the relative amounts of the elements, as oxides, abstracted from the rocks of the crust, by drainage waters, as compared with the amounts of the same oxides in the rocks. Obviously, this use of the word solubility is quite different from the strict sense, where a solution acts upon a homogeneous substance, without decomposition, but no other term expresses the idea as well, and such a usage is so familiar to geologists as to justify it in the present connection. A similar plea may be made for considering the oxides, the "chemical constituents" of rocks, as distinguished from the actual minerals. As before stated, these oxides are continually made the chemical units in the discussions of rocks, and this well-established custom necessitates, in the present discussion, the expression of water analyses in oxides rather than ions, as is the current custom. The use of ions for both classes of analyses would lead to the same results, but would, of course, be highly artificial, as well as unfamiliar, in the case of rocks.

[1] Cf. A. S. Cushman, and P. Hubbard, *The Decomposition of the Feldspars*, U.S. Department of Agriculture, Office of Public Roads, Bull. No. 28, p. 10, 1907.

That the constituents of rocks and minerals differ widely in their solubility is a familiar fact, made apparent by a superficial examination of rocks in the field, and emphasized by laboratory experiments, and the analysis of fresh and weathered rocks and of natural waters. As a result of investigations along these lines, it is well known that certain oxides, such as silica and alumina, are relatively resistant, while others, such as the alkalies and alkaline earths, pass somewhat readily into solution. Thus, orthoclase yields its alkalies in solution, while the silica and alumina remain in the solid state as kaolinite and quartz.

For our present purpose, this may be expressed simply as due to the greater solubility of the alkalies as compared with silica and alumina, ignoring the obvious fact that it is, in reality, a case of decomposition, not simple solution. It need hardly be said that the solubility (as the term is here used) of an oxide varies greatly with the compound in which it occurs, but the results of all such variations enter into the average relative solubility, as here discussed, without demanding any separate treatment.

Quantitative data in regard to solubilities are generally obtained by one of two very different methods. A definite amount of the rock or mineral is treated with a definite amount of water, the conditions varying with different experiments, and, by analysis of the resultant solutions, the relative amounts of the constituents dissolved are determined. This method is artificial, but, by a proper adjustment of the conditions of the experiment, may yield results of importance in interpreting natural phenomena.[1] The second method of acquiring quantitative data is to analyze fresh rocks or minerals and the corresponding residual clays or alteration products and, by a comparison of the results, to deduce the amounts of various constituents removed in solution. The first method has, thus far, been applied chiefly to minerals, but the second has been extensively applied to rocks, and has yielded results of great interest.

The two methods of investigation are essentially distinct and, while they supplement each other, do not yield strictly comparable results. In the first, or laboratory, method, a definite amount of

[1] Cf. W. P. Headden, "Significance of Silicic Acid in Waters of Mountain Streams," *Am. Jour. Sci.* (4) XVI (1903), 169–184.

the solid is treated with a definite amount of the solvent, equilibrium is established, and there is no further change of composition of either solid or solution. In nature, on the other hand, there is a continued renewal of the solvent, so that, while the most soluble constituents are first removed in relatively large quantities, the others must yield ultimately to repeated attack and the amount finally dissolved depends upon the length of time during which the process continues. Thus, to yield comparable results, the laboratory sample would have to be treated repeatedly with fresh supplies of solvent. However, this applies more especially to chemical weathering where residual clays accumulate to considerable depth and lie a long time. When secular elevation and erosion bring fresh rock within the range of solvent action, there is a tendency to compensate somewhat for the fresh supplies of solvent continually furnished, and thus to bring the conditions more nearly into harmony with those of the laboratory experiment. But an even closer approximation to the laboratory method is obtained if the entire mass of the crust traversed by meteoric waters is considered as a unit acted upon by the total body of drainage waters which, falling relatively pure upon the land areas, immediately begin to exert their solvent power and, ultimately, carry to the sea the different constituents of the crust, in varying amounts.

It was from this point of view that the problem was approached, when first considered, the composition of the crust and of the drainage waters being the basis of calculation. The former was afforded by Clarke's[1] familiar estimates of the composition of the outer shell of the crust and of the sedimentary rocks. Of the average composition of the drainage waters, only Sir John Murray's[2] preliminary estimate was available, and it was because of serious doubt as to the accuracy of these figures that publication of the results was abandoned.

While there is still much to be wished for in regard to data bearing upon the composition of drainage waters, the last few years have afforded sufficient added information in this direction to warrant renewed consideration of the problem.

[1] F. W. Clarke, *Bull. U.S. Geol. Surv.*, *228*, p. 19.

[2] Sir John Murray, *Scottish Geog. Mag.* (1887), p. 76.

In the present paper, the essential data used are Clarke's later estimates of the composition of the crust, and the same author's estimated mean composition of river waters.[1] The results obtained from these data are supplemented by data from other sources, as shown below.

ABUNDANT CONSTITUENTS OF ROCKS DISSOLVED IN RIVER WATERS (RECALCULATED TO 100)

	Clarke's Mean for Rivers of the Earth*	Mississippi River†	Ottawa River‡	Cache à la Poudre (Colo.)§	Feldspar Solution¶
CaO	48.34	51.05	37.12	31.12	14.43
Na_2O	14.61	16.45	9.73	21.48	7.39
MgO	9.55	15.86	12.57	7.22	1.08
K_2O	3.09	3.44	3.02	4.89	15.45
SiO_2	19.76	12.52	31.97	34.64	57.41
R_2O_3	4.65	0.68	5.59	0.65	4.24
	100.00	100.00	100.00	100.00	100.00

* Clarke's mean for the abundant constituents of the rivers of the earth.
† Mississippi River water, with Na_2O and K_2O calculated at the ratio of 4.24 to 1. Analysis by J. L. Porter. Annual average of Dole and Stabler as quoted by Clarke, *op. cit.*, p. 3.
‡ Ottawa River. Analysis by F. T. Shutt, published by R. A. Daly.
§ Cache à la Poudre, Colorado, Analysis by W. P. Headden.
¶ Feldspar Solution. Analysis by W. P. Headden.

The above constituents were recalculated to 100 per cent in order that their relative amounts in the different waters might be readily compared. For the rock analyses this was unnecessary, as the abundant constituents predominate so markedly that their amounts would be little changed by such recalculations, while, for determining the relative solubilities, it is not needed.

ABUNDANT CONSTITUENTS OF ROCKS

	Igneous Rocks*	Sediments†	Lithosphere‡	Surface Rocks§	Pike's Peak Granite¶	Feldspar**
CaO	4.81	5.42	4.82	5.27	0.74	0.314
Na_2O	3.41	1.12	3.28	1.69	3.10	2.728
MgO	3.89	2.52	3.98	2.86	.07	0.029
K_2O	2.95	2.80	2.96	2.84	5.92	11.592
SiO_2	59.99	58.51	59.79	58.88	74.90	65.760
R_2O_3	21.34	18.69	21.25	19.35	14.48	19.291

* Abundant Constituents in Clarke's estimated average Igneous Rock, *Op. Cit.*, p. 13.
† Abundant Constituents in Clarke's estimated average Sediment, *Ibid.*
‡ Abundant Constituents in Clarke's estimated average Lithosphere, *U.S. Geol. Surv. Bull. 330*, p. 31.
§ Estimated composition of "Surface Rocks," derived by combining Igneous Rocks and Sediments in the ratio of one to three.
¶ Average of Analyses of four granites from Pike's Peak Quadrangle by W. F. Hillebrand, *Journal of Geology*, VIII, 237.
** Analysis of Feldspar, Horsetooth, Col. by W. P. Headden, *op. cit.*, p. 181.

[1] F. W. Clarke, *A Preliminary Study of Chemical Denudation*, Smithsonian Coll., Vol. LVI, No. 5, p. 8, 1910.

Were the various constituents of rocks equally susceptible to the action of drainage waters,they would be carried to the sea in the proportions in which they occur in the crust. That this is far from being the case is a most familiar fact, and it is evident that they go into solution at very different rates. These rates are expressed by the ratios between the amounts of the various constituents in the rocks and in the drainage waters, respectively. That these relative rates must vary widely in different cases there can, of course, be no doubt, but the average rates are simply determined by the comparison of the compositions of the surface rocks and of the drainage waters. For the latter, Clarke's "General Mean"[1] is taken, column I, using, as in all other cases, only those constituents that are abundant in rocks.

For the rocks, the simplest method is to take Clarke's average composition of the lithosphere,[2] but this introduces an obvious source of error. This average represents a shell ten miles thick, of which probably 95 per cent consists of igneous rock. Drainage waters, being relatively superficial, exert their influence on rocks that are probably 75 per cent sedimentary and have lost certain constituents, particularly sodium, now held in solution in the sea. For this reason, it is necessary to use, as the basis of calculation, figures that allow for this permanently dissolved material. Moreover, in so far as the elements in sediments are combined differently from what they were in the crystalline rocks, their relative solubilities are doubtless affected. Correct results are to be obtained only by comparing the composition of river waters with that of the actual materials of their basins, and in the absence of precise data, the closest approximation possible must be sought.

This has been done by taking Clarke's "weighted mean"[3] of the composition of sedimentary rocks and his estimate of the composition of igneous rocks[4] and combining them in the ratios of three to one, in accord with Von Tillo's estimate of the relative areas of sedimentary and igneous rocks, the results appearing in

[1] *Op. cit.*, p. 8.

[2] "The Data of Geochemistry," *U.S. Geol. Surv. Bull., No. 330*, p. 31.

[3] F. W. Clarke, *A Preliminary Study of Chemical Denudation*, Smithsonian Misc. Coll., Vol. LVI, No. 5, p. 13, 1910.

[4] *Loc. cit.*

column II and called "surface rocks." These figures are assumed to represent the composition of the rocks leached by drainage waters, and, compared with the mean composition of the latter, column I, give the average relative solubilities of the abundant constituents of the earth's crust.

The latter values are represented by the ratios between the constituents in the water and the corresponding constituents in the rocks. These values appear in columns III and IV, in the latter recalculated to a basis of lime = 100, lime having the highest relative solubility, being an abundant constituent, and readily determined with accuracy.

The constituents are written in the order of relative solubility beginning with CaO.

	I Clarke's Mean River Water	II Surface Rocks	III Rel. Solubilities	IV Rel. Solubilities (CaO = 100)
CaO	48.34	5.27	9.17	100.0
Na_2O	14.61	1.69	8.64	96.1
MgO	9.55	2.86	3.34	36.3
K_2O	3.09	2.84	1.09	11.9
SiO_2	19.76	58.88	0.34	3.7
R_2O_3	4.65	19.35	0.24	2.6

Thus, assuming the accuracy of the figures in columns I and II, it follows that the abundant oxides of the crust are dissolved at relative rates represented by the figures of columns III and IV. Lime and soda appear to be dissolved at about the same rate, magnesia at about one-third this rate, potassa again about one-third as fast as magnesia, silica about a third as fast as potassa, and the sesquioxides about two-thirds as fast as silica. How far these figures may be trusted depends, obviously, upon the reliability of the estimated composition of river waters and of surface rocks. That these estimates will be modified in future is beyond question, and any change will, of course, affect the values of the relative solubilities. But it is believed that the figures given are a fairly close approximation to the true values, indicating, at least, the proper orders of magnitude. The most questionable figure is that for soda, since it is this constituent that is largely retained in the ocean and least likely to be accurately estimated in sediments,

where the number of analyses is limited. The other constituents cannot differ much in relative amounts in sediments and in igneous rocks. Van Hise[1] has pointed out, and explained, certain discrepancies when the analyses of the sediments are compared with those of the igneous rocks, but for the present purpose these may be overlooked. However, in view of the possible divergence of the compositions of sediments used from the true mean, it may be worth while to make a similar calculation using the composition of the igneous rocks, instead of that of the surface rocks, as above estimated. It is probable that this composition of the igneous rocks is more accurate than that of the sediments which was introduced in calculating the composition of the surface rocks, and, except for the soda, fairly accordant results might be expected, although as pointed out above, the surface rocks must differ from igneous rocks not only in bulk composition but also as to compounds present, and a comparison of the composition of drainage waters with that of the igneous rocks is, therefore, highly artificial. The results of such a comparison of the mean composition of river waters with that of the average composition of igneous rocks, are as follows:

	V Clarke's Mean River Water	VI Igneous Rocks	VII Solubilities	VIII Solubilities ($CaO=100$)
CaO	48.34	4.81	10.05	100.00
Na_2O	14.61	3.41	4.28	42.5
MgO	9.55	3.89	2.46	24.5
K_2O	3.09	2.95	1.05	10.4
SiO_2	19.76	59.99	0.33	3.3
R_2O_3	4.65	21.34	0.22	2.0

Comparing the figures of columns VII and VIII with the corresponding figures of columns III and IV, the expected relations are seen, substantial agreement except for soda which shows, in column VII and VIII, decidedly smaller relative solubility. This must necessarily be the case, since the river waters actually derive their soda largely from the already depleted sediments, and if, as here done, their content be compared with that of the unleached igneous

[1] C. R. Van Hise, "Treatise on Metamorphism," *Monograph* XLVII, *U.S. Geol. Surv.* (1904), chap. xi.

rocks, a much lower, and essentially abnormal relative solubility must be obtained. While there is a tendency in the same direction for MgO, it is too slight to account for the lower figure. The fairly good agreement of the other constituents is an argument in favor of the essential reliability of the data used for the calculation, and gives added confidence in the relative solubilities of columns III and IV.

It is evident that, on the basis of solubility, the constituents fall into four distinct groups; lime and soda, magnesia and potassa, and silica and sesquioxides, although potassa might be classed with the last two, making only three groups.

It is unfortunate that alumina and iron oxide cannot be estimated separately, particularly with reference to the history of the sedimentary iron ores, but in the analyses of river waters used as the basis of calculation, they are determined together and, thus, cannot be separated here. Furthermore, these constituents occur in small quantity in waters, are difficult to determine accurately and, therefore, even when taken together, their relative solubility is open to question, although its order of magnitude is clearly fixed.

The figures of columns III and IV, then, in so far as they are accurate, express a most general relation existing between the chief chemical constituents of rocks with reference to their behavior under the solvent action of drainage waters. Based, as they are, upon analyses of the present surface rocks and existing rivers, they hold good only for existing conditions: petrologic, topographic, and climatic. A marked change of any of these conditions would produce a corresponding change in the relative solubilities, and there can be no doubt that many such changes have occurred. Doubtless, on the average, the divergence from existing values was greatest in the most remote geological times, and this must be taken into account in all considerations of chemical denudation in earlier periods. However, it is obvious that the intervals between the solubilities of the four groups are of such magnitude as to allow of considerable range, without changing the order, so much so as to make it not unlikely that the order has been the same throughout geological time.

This order, it may be noted, is in general agreement with the

order of amounts dissolved derived from the study of weathering and its solid products, as shown by Merrill,[1] Van Hise[2] and others, although that method gives no numerical relation, and its generalizations are commonly based chiefly upon igneous rocks. Van Hise calls attention to the fact that the different constituents are removed in surprisingly similar amounts, but this, of course, concerns the end result, and takes no account of relative rates of solution. As pointed out earlier, the more soluble constituents go first, so there is an ever-present tendency toward the relative concentration of the constituents of low solubilities, silica and the sesquioxides and, to a less degree, potash, in the residual clays. Were there no mechanical erosion a certain kind of equilibrium might be reached, in which residual clays would have practically uniform compositions (varying with climatic conditions) not changing with further solution. That there is a tendency to such a condition is emphasized by a comparison of the composition of residual clays, showing as they do, striking resemblances, with the widely divergent composition of rocks.

It is believed that the above figures for relative solubilities are of sufficient interest in themselves to warrant their publication, while they touch upon many problems in connection with weathering, chemical denudation, metamorphism, etc. Even upon so large a theoretical question as the composition and density of continental and oceanic areas, as discussed by Chamberlin and Salisbury,[3] they have a bearing.

While it is true that the relative solubilities given above express only a most general relation, and cannot be applied to a specific case, the simple method of comparison can be used, wherever the necessary data are available, with instructive results. From the widely varying compositions of streams and of the rocks of their drainage basins, it is clear that most divergent results must be obtained. It is only as the conditions approach the average for the entire land area that any close approximation to the mean solubilities may be expected. A few cases are appended by way of illustration.

[1] G. P. Merrill, *Rocks, Rock Weathering and Soils* (1906), p. 220.

[2] C. R. Van Hise, *op. cit.*

[3] *Geology*, II, 107.

The composition of the Mississippi River water, so far as the abundant oxides are concerned and with the soda and potassa calculated according to Clarke's[1] ratio, is given in IX, calculated to 100 from Dole and Stabler's analysis. Clarke's[2] average composition of sediments is assumed to represent the composition of the Mississippi basin. The resulting relative solubilities appear in columns XI and XII:

	IX Mississippi River	X Average Sediments	XI Solubilities	XII Solubilities (CaO = 100)
CaO.........	51.05	5.42	9.6	100.0
Na_2O........	16.45	1.12	14.7	152.8
MgO.........	15.86	2.52	6.3	65.5
K_2O.........	3.44	2.80	1.2	12.5
SiO_2.........	12.52	58.51	.214	2.2
R_2O_3.........	0.68	18.69	.036	0.4

Compared with the figures of column VIII, there is a striking increase in the solubility of soda and magnesia. In other words, these two constituents are notably abundant in Mississippi water as compared with the amounts in the rocks, if these latter are accurately represented by the analyses used. If they are too low in the estimate used, the solubilities would come nearer the mean values. Potassa and silica are in fair accord with the mean, while the sesquioxides are low. On the whole, however, the agreement is surprisingly close in view of the fact that a single river basin is concerned, even though it be of a rather generalized type.

Another case, representing quite different conditions, is afforded by the Ottawa River, draining an area of crystalline rocks. The composition of the dissolved salts, as given by Daly[3] and recalculated to 100 per cent of abundant oxides, is shown in column XIII.

Clarke's[4] estimate of the mean composition of the lithosphere is taken to represent the composition of the Ottawa's drainage basin, column XIV, although the assumption is recognized as a rather sweeping one.

[1] *Op. cit.*, p. 9. [2] *Op. cit.*, p. 13.

[3] R. A. Daly, "First Calcareous Fossils and the Evolution of Limestones," *Bull. Geol. Soc. Am.*, XX (1909), 158.

[4] "The Data of Geochemistry," *U. S. Geol. Surv. Bull., No. 330*, p. 31.

The resultant relative solubilities are given in columns XV and XVI.

	XIII Ottawa River	XIV Average Crust	XV Solubilities	XVI Solubilities (CaO = 100)
CaO.........	37.12	4.82	7.70	100.
Na_2O........	9.73	3.28	2.96	38.5
MgO.........	12.57	3.98	3.16	40.1
K_2O.........	3.02	2.96	1.02	13.4
SiO_2.........	31.97	59.79	.53	6.9
R_2O_3.........	5.59	21.25	.26	3.4

These figures approach most closely to those derived from comparison of the mean river water with the average igneous rocks, and differ most widely from those derived from the Mississippi River and average sediments.

The most striking variation is in the soda, which, instead of being close to lime in solubility, falls below, but close to, magnesia, thus changing the solubility groups. It is interesting to note that this order of relative solubility is the same as the order of percentage loss for each constituent for a group of nine crystalline rocks, as given by Van Hise.[1]

It would seem to be a necessary inference that, on the average, the silicates of the alkaline earths and sodium are more readily decomposed than those of potassium, aluminum and iron.

Without placing too much dependence upon either case, it seems safe to conclude that the figures for the Ottawa River roughly represent the relative solubilities for crystalline regions, while those for the Mississippi roughly represent the relative solubilities for sedimentary regions.

It is rather surprising to find the relative solubilities of soda and magnesia greater in sediments than in crystallines. While this may be due in part to the presence of more soluble compounds the essential reason probably is afforded by the rule elsewhere pointed out that, as a constituent decreases in absolute quantity in the rocks, its relative solubility increases.

The average of the solubilities derived from the Mississippi and the Ottawa is given in column XVII and the weighted mean,

[1] *Op. cit.*, p. 516.

taking the values for the Mississippi and the Ottawa in the ratio of three to one, is given in column XVIII.

	XVII	XVIII
CaO	100.0	100.0
Na_2O	95.6	124.2
MgO	52.8	59.1
K_2O	12.9	12.7
SiO_2	4.5	3.4
R_2O_3	1.9	1.1

Representing roughly the relative areas of crystalline and sedimentary rocks, the figures in column XVIII must be compared with those of IV.

The same groups appear in column XVIII, but owing to the high figure obtained for soda in the Mississippi water this constituent has changed places with lime as most soluble, while, for a similar reason, magnesia gives an abnormally high figure. Nevertheless, when the nature of the data used is considered, the agreement between these special cases and the general case is as close as could be expected.

What widely different relative solubilities may prevail in an individual case, which does not approximate to the general conditions, is shown by the waters of the Cache à la Poudre of Colorado, as analyzed by Headden[1] when compared with the average of four granites, from Pike's Peak Region, analyzed by Hillebrand,[2] which may be taken as fairly representing the stream basin.

	XIX Cache à la Poudre	XX Pike's Peak Granite	XXI Solubilities	XXII Solubilities (CaO = 100)
CaO	31.12	0.74	42.05	100.0
Na_2O	21.48	3.10	6.91	16.4
MgO	7.22	0.07	103.14	244.4
K_2O	4.89	5.92	0.84	2.0
SiO_2	34.64	74.90	0.49	1.0
R_2O_3	0.65	14.48	0.05	0.1

A mere glance at the two analyses (XIX and XX) shows a notably high content of lime and magnesia in the water as com-

[1] *Loc. cit.*

[2] E. B. Mathews, "Granite Rocks of the Pike's Peak Quadrangle," *Journal of Geology*, VIII, 237.

pared with the composition of the granite, and this is accentuated by the figures for relative solubilities (XXI and XXII).

Even the groups have been changed, and magnesia has gone far ahead, not only of soda, but also of lime, becoming conspicuously the most soluble constituent. The remaining four constituents have relative solubilities not widely different from the normal, and if multiplied by five give soda 82, potash 10, silica 5, and sesquioxides 0.5. Such divergences from the average results are only what is to be expected, indicating, as they do, how local conditions control the action of drainage waters.

Headden has laid stress upon the high silica content of this water, in which respect it is remarkable, and not only is the content of silica high, but the relative solubility is also high, as compared with soda, potash and the sesquioxides. But, from the present point of view, the striking feature is not the silica content but the relatively great lime and magnesia content, implying high relative solubilities.

As in the case of soda in the sediments, but to a much more pronounced degree, low content of lime and magnesia is accompanied by high relative solubility, and it seems probable that this relation is a general one.

This relation is particularly suggestive in connection with the problem of ore deposits, where it is always so difficult to account for the concentration, into workable bodies, of minute quantities of disseminated metals. If the 0.74 per cent of lime and 0.07 per cent of magnesia can, by the differential solvent power of drainage waters, be concentrated to 31.12 per cent and 7.22 per cent, respectively, of the abundant oxides in the water, it is safe to assume that the much less abundant metals of rocks may undergo an analogous and, perhaps, even greater, concentration, by underground waters, either meteoric or magmatic. Perhaps this relation becomes more apparent if the relative solubilities of lime and magnesia are multiplied by five, as the others were to bring them up to the normal numbers. In this case the solubility of lime is 500 and that of magnesia is 1,222.

Of course, in the ore deposit problem, it is of vital importance to know what compounds of the metals are involved, but, in spite

of the absence of such knowledge, it seems fair to infer that the minute quantities of metals that have sometimes been determined in rocks of mining districts have, because of their small quantities, higher relative solubilities than the other constituents of the rocks and thus take the first step, and perhaps a long one, toward their final concentration, when they go into solution in ground waters. The same doubtless applies to the rarer gangue materials as well.

One further special case may be added, particularly because it affords positive data as a basis of calculation, which were lacking in all the preceding cases. Reference is made to Headden's[1] experiments upon the solution of feldspar in carbonated water.

The powdered feldspar was treated with successive portions of distilled water for 48 hours, agitation being effected by a current of air containing a little carbon dioxide. Nearly 35 gallons of water were used, evaporated to dryness, and the residue analyzed. The results appear in column XXIII, the composition of the feldspar in XXIV, and the relative solubilities in columns XXV and XXVI.

	XXIII Feldspar Solution	XXIV Feldspar	XXV Solubilities	XXVI Solubilities ($CaO=100$)
CaO	14.43	0.314	45.95	100.0
Na_2O	7.39	2.728	2.70	5.9
MgO	1.08	0.029	37.24	80.8
K_2O	15.45	11.592	1.33	2.9
SiO_2	57.41	65.760	0.87	1.9
R_2O_3	4.24	19.291	0.22	0.5

The agreement with the Cache à la Poudre figure is not as close as might be expected, the magnesia here occupying second place instead of first.

The relative solution concentration of magnesia, is less pronounced, for if all the figures be multiplied by five, while it gives high results for potassa, silica, and sesquioxides, the magnesia becomes only 404 as compared with 1,222. Still, the abnormally high relative solubility for constituents in small quantity is again illustrated. On the other hand, potassa shows no reduction of relative solubility as compared with soda, silica and sesquioxides,

[1] *Op. cit.*, p. 181.

in spite of its high percentage in the feldspar, while soda, present in normal quantity, is conspicuously low in relative solubility.

The wide divergences from mean relative solubilities shown by this experiment are to be accounted for on two grounds. In the first place, the conditions of the laboratory only roughly reproduced those of nature; while, in the second place, the feldspar varies rather widely from the mean composition of the rocks. The former fact may account for the relatively high solubility of potash, in spite of its large amount in the feldspar, and the low figure for soda, while the latter is doubtless responsible for the high figures for lime and magnesia.

It would be interesting to see what results would be yielded by similar experiments upon rocks representing the average surface, crystalline areas, etc., and the writer hopes that such experiments may be carried out in future. Meanwhile, the foregoing figures are presented not because they are regarded as important in themselves but rather as suggesting a promising line of investigation.

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THE COBALT SERIES; ITS CHARACTER AND ORIGIN[1]

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INTRODUCTION

In that part of northern Ontario and Quebec of which Lake Timiskaming is the geographical center, a series of pre-Cambrian clastic sediments occur which are of peculiar interest to the geologist, not only because they form the country rock of the larger part of the rich silver-bearing veins of the Cobalt mining camp, but because, as is shown in the following pages, their character is such as to indicate that they are entirely of terrestrial origin and have been deposited in part from continental glaciers. If the foregoing conclusion be correct, then another glacial period more ancient than any of those yet described in other parts of the world is added to our knowledge of the geological history of the earth, and positive evidence is afforded as to the remarkable uniformity of geological processes even in pre-Cambrian times.

In order to reach a logical conclusion as to the manner in which any series of rocks has been deposited, full information as to the character and geological relationship of the series as a whole and of all its members is necessary. The following discussion is therefore divided into two parts, in the first of which the geological relations and lithological character of the Cobalt series is described, and in the second, an application is made of those criteria from which the mode of origin of the various members of the series may be inferred.

GEOLOGICAL RELATIONS AND CHARACTER OF THE COBALT SERIES

GENERAL GEOLOGY OF THE TIMISKAMING REGION

Geologically this region belongs to the great Canadian shield of pre-Cambrian rocks which occupies the greater part of north-

[1] Published by permission of the Director of the Geological Survey branch of the Department of Mines, Canada.

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eastern North America, and corresponds in general to the Lake Superior–Lake Huron geological province. In a structural way, the rocks of the Timiskaming region may be divided into three elements which are strikingly differentiated from one another: to the first of these belong the older complex; to the second the Cobalt series (Huronian) and Nipissing (Keweenawan) diabase; and to the third the Pleistocene and Recent deposits.

The first subdivision, the older complex, consists of two classes of rocks: (1) the surficial, consisting of basic to acid volcanic flows, conglomerate, greywacke, arkose, and slate; and (2) the plutonic, consisting of granite, granodiorite, diorite, and related rocks. The rocks of the second class, as far as has been observed, are intrusive into the surficial class although the presence of pebbles and bowlders of granite in the conglomerate shows conclusively that an older granite occurs somewhere in the region and that a great erosion interval is represented.

From an examination of a general geological map of northeastern Canada, it may be seen that a wide belt of granite and related rocks (Laurentian) extends continuously from Georgian Bay to the Gulf of St. Lawrence, while to the north of this, there is a belt in which rocks of the surficial class predominate and which extends from the north shore of Lake Huron to Lake Mistassini. It seems probable that the southern granitic belt represents an ancient geanticlinal mountain core and the adjacent belt on the north a geosynclinal intermontane belt, but denudation proceeded so far in pre-Cambrian times that this synclinorium was cut off close to its base so that the surficial members of the complex are intruded by numerous small isolated batholiths of granitic rocks which have effected marked local changes in the structural trend of the rocks in their vicinity.

On the profoundly denuded surface of this ancient complex lies the second structural element, the Cobalt series (Huronian). In striking contrast with the complicated plications of the older element, the structure of these rocks is comparatively simple. They have been very slightly folded into broad, gently pitching anticlines and synclines, the dip being usually less than 20 degrees.

Along with the older complex the Cobalt series is intruded by the Nipissing (Keweenawan ?) diabase which took the form of dikes in the older basement but spread out as sills in the flat-lying Huronian sediments.

The third structural subdivision, the Pleistocene and Recent deposits consist of gravel, sand, and bowlders, in the various forms assumed by glacial and fluvioglacial materials, and stratified clay and sand of postglacial lacustrine origin. These rest on the beveled surface of the Cobalt series or on the truncated surface of the older complex from which the Cobalt series has been stripped away.

THE COBALT SERIES

GENERAL CHARACTER AND SUBDIVISIONS

The Cobalt series consist of an assemblage of clastic sediments, conglomerate, greywacke, argillite,[1] arkose, and quartzite. These rocks are not sharply defined members, for they not only pass gradationally into one another, both horizontally and vertically, but conglomerate commonly occurs in the midst of greywacke or greywacke in the midst of conglomerate, and a similar relationship may exist between all the members of the series. Nevertheless, in a general way, there is a succession in most localities, from a basal conglomerate through greywacke and argillite to arkose, which in turn is overlain by an upper conglomerate.

A compilation of all the published observations of the succession and thickness of the various rocks comprising the series throughout the Timiskaming region is given in the accompanying table. Many of these sections are evidently only partial, including in some cases the upper members and in others the middle or lower. It can be seen, however, that there is generally an upper and lower conglomerate with greywacke and argillite, quartzite, and arkose as intermediate members.

[1] At the suggestion of Dr. L. V. Pirsson, the term argillite is here redefined to designate a fine grained slate-like rock which has been very firmly cemented but has no slaty cleavage. Its position in the mud-slate series corresponds very closely to that of quartzite in the sand-sandstone group.

SECTIONS OF THE COBALT SERIES IN THE TIMISKAMING REGION, ONT. AND QUE.*

Rock	Thickness	Locality	Reference
Quartzite, etc........ Slate and greywacke Conglomerate.......	1,100 feet 100 " 600 "	Timiskaming district	A. E. Barlow, *Rep. Can. Geol. Surv.*, X (1897), 104.
Slate†.............. Conglomerate.......	? ?	Between Rabbit and Timagami lakes	G. A. Young, *Sum. Rep. Can. Geol. Surv.* (1904), p. 198.
Conglomerate....... Quartzite...........	? ?	Cobalt, Ont.	W. A. Parks, *Sum. Rep. Can. Geol. Surv.* (1904) p. 211.
Quartzite, etc........ Slate† and greywacke	90 " 90 "	Windigo Lake	W. A. Parks, *ibid.*, p. 215.
Conglomerate....... Quartzite........... Slate†..............	100 " 135 " 315 "	Mount Shiminis	W. A. Parks, *ibid.*, p. 220.
Conglomerate....... Quartzite........... Greywacke.......... Conglomerate.......	? ? ? ?	Cobalt, Ont.	W. G. Miller, *Ann. Rep. Bur. Mines, Ont.* (1905), Pt. 2, p. 34.
Conglomerate....... Quartzite........... Slate†.............. Quartzite........... Conglomerate.......	? ? ? ? ?	Larder Lake, Ont.	R. W. Brock, *ibid.*, (1907), p. 211.
Conglomerate....... Greywacke and slate†	? ?	Claims H.R. 34 and 163 South Lorain.	A. G. Burrows, *ibid.* (1908), Pt. 2, p. 24.
Slate†.............. Quartzite........... Conglomerate.......	? ? ?	Everett Lake Gowganda dist.	A. G. Burrows, *ibid.*, p. 10.
Conglomerate....... Slate†..............	? ?	Bloom Lake	A. G. Burrows, *ibid.*
Conglomerate, etc.... Greywacke quartzite Conglomerate.......	? ? 200+"	Gowganda dist.	W. H. Collins, *Prelim. Rep. on Gowganda Dist.*, pp. 26 and 27; *Geol., Surv., Dept. of Mines, Can.* (1909.)
Greywacke arkose,etc. Conglomerate.......	? ?	Montreal river district	W. H. Collins, *Sum. Rep. Geol. Surv., Dept. of Mines* (1910), p. 199.
Conglomerate.......	750 "	Kekeko hills Pontiac County, Que.	M. E. Wilson, *Prel. Mem. on Abitibi Dist., Que.*

* Sections are in descending order.

† The term slate is used for a slate-like rock without slaty cleavage—argillite.

SECTIONS OF THE COBALT SERIES IN THE TIMISKAMING REGION, ONT., AND QUE.—*Continued*

Rock	Thickness	Locality	Reference
Arkose	220 "	North end Lake Opasatika, Pontiac Co., Que.	M. E. Wilson, *ibid.*
Conglomerate	80 "		
Arkose	250 "	Swinging Hills, Pontiac Co., Que.	M. E. Wilson, *ibid.*
?	365 "		
Conglomerate	70+"		
Conglomerate	65 "	Labyrinthe Hills Pontiac Co., Que.	M. E. Wilson, *ibid.*
Arkose	165 "		
?	175 "		

Basal conglomerate.—Wherever the Cobalt series is seen in contact with the rocks of the older complex, the basal member of the series is usually a conglomerate. The outstanding feature of this basal conglomerate is its heterogeneity, not only in the size and angularity of the included fragments, but in the variability of the rock, both in texture and composition from point to point. In some places it is largely composed of coarse fragmental material with little matrix and, in other places, consists largely of matrix with few fragments. As a rule it is unstratified, but locally a partial alignment of the pebbles can be seen.

The matrix of the conglomerate varies greatly in texture and composition and may be either coarse and feldspathic or exceedingly fine grained and slate-like in appearance; the coarser types are, however, by far the most common. Examined under the microscope the matrix is seen to be composed of angular, subangular, and round fragments of quartz, feldspar, quartz porphyry, mica schist, rhyolite, andesite, basalt, and other rocks inclosed in a cement consisting chiefly of chlorite, but usually accompanied by small quantities of carbonate, epidote and pyrite (Figs. 1 and 2).

The pebbles and bowlders of the conglomerate include, even in a single rock exposure, nearly every variety of rock occurring in the older complex. Fragments of granite occur everywhere, and are commonly many miles from the nearest occurrence of this rock in the underlying basement from which the Cobalt series was evidently derived. As is generally characteristic of coarsely

clastic sediments of this character, the pebbles and bowlders are commonly subangular or angular in shape though round fragments are also present.

Greywacke and argillite.—The basal conglomerate of the Cobalt series commonly passes gradually upward by the loss of its pebbles and bowlders into greywacke and argillite. This greywacke was originally a ferromagnesian sand and the argillite a ferromagnesian mud, both of which are now, however, very firmly cemented, the

FIG. 1.—Photomicrograph of conglomerate matrix. Ordinary light. ×20

argillite resembling a slate but differing from a slate in possessing no slaty cleavage. The greywacke and argillite, like the other members of the Cobalt series, vary greatly, and here and there contain beds of arkose, masses of conglomerate, and, in some places, single isolated bowlders. In a few places the greywacke is unstratified, but as a rule both it and the argillite are uniformly bedded. The microscopic examination of the greywacke shows it to consist of fragments of quartz, feldspar, basalt, andesite, and other ferromagnesian rocks along with an abundance of chlorite.

The argillite is much finer grained than the greywacke, consisting of exceedingly minute fragments of quartz and feldspar imbedded in a chloritic cement. Small quantities of sericite, epidote, and carbonate are also commonly present in all of these rocks.

Arkose and quartzite.—The greywacke and argillite are usually replaced on passing upward by arkose or quartzite, the transition taking place by a gradual increase in the feldspar and quartz content or by an alteration of beds of the two rocks. The arkose

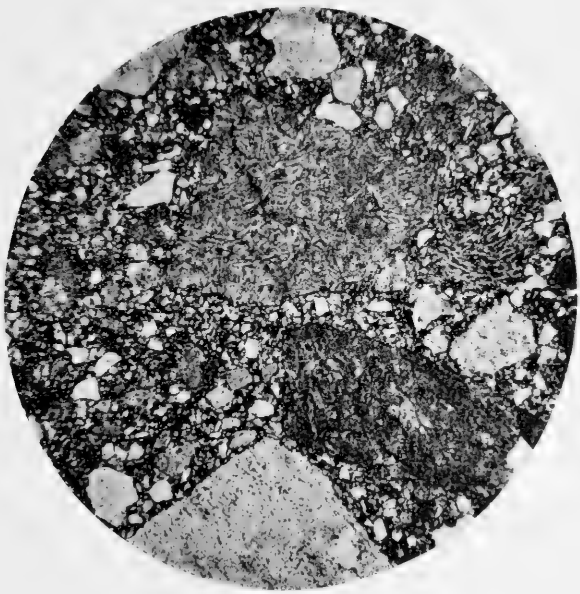

FIG. 2.—Photomicrograph of conglomerate matrix. Crossed nicols. ×20

and quartzite are firmly cemented sands which, when examined under the microscope, are found to consist of round, angular, or subangular fragments of quartz, or of quartz and feldspar along with small quantities of calcite, sericite, epidote, pyrite, and other minerals. They are generally stratified, may show ripple marks, are locally cross-bedded, and in places contain well-rounded pebbles of quartz and jasper in lenticular aggregations.

Upper conglomerate.—Wherever the Cobalt series has a considerable vertical thickness, the arkose and quartzite are overlain

conformably by an upper conglomerate which differs in no respect from the lower member of the series and cannot be distinguished from it except where the stratigraphical succession is known.

INTERFORMATIONAL UNCONFORMITIES

In his geological report on the Cobalt district, W. G. Miller subdivided the Cobalt series into Lower and Middle Huronian,[1] but more recently[2] has adopted the name Cobalt series to include both these subdivisions. Miller's classification of the Huronian into two series was based on an unconformity between greywacke and arkose occurring, on lot 4, in the twelfth concession of Lorrain Township, Nipissing district, Ontario, where angular fragments of the greywacke are inclosed in an arkose matrix. Unconformities between a "greywacke conglomerate and an overlying arkose series" are also mentioned by A. G. Burrows in a marginal note on a map of "part of the Gowganda silver area," published by the Ontario Bureau of Mines, but no details as to the character of these are given. In one locality in the Larder Lake district the writer observed an arkose bed to contain fragments of an underlying argillite, but the fragments were irregular in outline and contained sand grains along their margin as if the argillite had been plastic at the time of its fragmentation. Fragments of a precisely similar character and in the same relationship have also been observed by W. H. Collins in the region north of the Sudbury district.[3] With the foregoing exceptions, as far as has been observed, the various members of the series are in conformable relationship to one another[4] so that the unconformities that have been described are local and probably interformational in character and do not necessarily signify a break of any importance in the continuity of deposition.

DISTRIBUTION OF COBALT SERIES

The Cobalt series is now known to occur in the Timiskaming region and vicinity throughout an area of approximately 20,000

[1] *Ann. Rep. Bur. of Mines, Ont.* (1905), Pt. 2, pp. 40–42.

[2] *Eng. Min. Jour.*, XCII (1911), 648.

[3] Personal communication.

[4] *Sum. Rep. Geol. Surv., Dept. of Mines, Can.* (1906), p. 117; "Geol. of an Area Adjoining the East Side of Lake Timiskaming," *Geol. Surv., Dept. of Mines, Can.* (1910), p. 30; "Prel. Rep. on Gowganda Mining Division," *ibid.* (1909), p. 32.

square miles, but this is probably a mere fraction of its former extent for much Huronian, having the same lithological character and geological relationships, occurs in outlying districts such as that on Lake Chibougamau, about 300 miles to the northeastward.

THE PRE-COBALT SERIES PALEOPLAIN

Since the rocks comprising the Cobalt series have been but very gently folded, it follows that the surface upon which they were deposited has also not been greatly deformed, and that by the study of the contours of the contact of the basal conglomerate and the older complex, the stage, in physiographic development of the ancient erosion surface, at the time the deposition of the Cobalt series began, may be deciphered. The approximately uniform elevation, at which the junction of the Cobalt series and the older complex occurs throughout considerable areas, shows that the topography of the ancient surface was generally flat, but here and there hills consisting of rocks of the older complex occur which rise to elevations of 200 to 600 feet above the surrounding country and which must have had a still higher elevation prior to the deposition of the Cobalt series, for they have undergone denudation since that series was stripped from their surface. The ancient surface had therefore a range in elevation as great or greater than that of the region at present, but on the whole was probably more flat, the hills being local remnants which rose above the general level of erosion. This pre-Cambrian surface of denudation, therefore, represents a peneplain buried and later exposed and falls into the class of form known as a paleoplain.

THE CONTACT OF THE COBALT SERIES AND THE OLDER COMPLEX

The contact between the Cobalt series and the rocks of the older complex is peculiar in places, in that no definite line of junction can be seen, the underlying rock passing gradually upward into the basal conglomerate; in other places, however, the contact is very sharply defined, the conglomerate resting on a smoothly denuded surface. A striking example of this transitional relationship occurring at Baie des bères on the east shore of Lake Timiskaming has been described in detail by Barlow

and Ferrier.[1] Examples of the sharply defined contacts have been described by W. H. Collins and by the writer.[2]

THE ORIGIN OF THE COBALT SERIES

HYPOTHESES PROPOSED

The Cobalt series has, in recent years, been the object of special study by those geologists engaged in fieldwork in the Timiskaming region for the purpose of procuring evidence which would confirm or disprove the glacial hypothesis which has been strongly advocated by A. P. Coleman in a number of recent publications.[3] With this object in view, the writer, while in the field, paid special attention to those characteristics of the various members of the series which might have a bearing on the conditions under which they were deposited, hoping in that way to reach some definite conclusions as to their origin.

That the conditions under which the series was deposited were unusual is indicated by the various modes of origin which have been suggested from time to time, by the geologists who have studied these rocks in the field. Owing to the fact that the earlier geologists did not distinguish the Cobalt series from the underlying Abitibi group[4] (Keewatin), the conglomerate was thought to be closely related to the lavas of the underlying basement and were said to be of pyroclastic origin,[5] although it was noted that many fragments of granite and other plutonic rocks were present. In 1905, A. P. Coleman in his report[6] on the Sudbury nickel field,

[1] "On the Relations and Structures of Certain Granites and Associated Arkoses on Lake Timiskaming, Canada," *Rep. B.A.A.S.*, Toronto (1897), pp. 656–60; *Ann. Rep. Geol. Surv. Can.* (1897), pp. 195–99, I.

[2] "Prel. Rep. on Gowganda District, Ont." *Geol. Surv. Bran., Dept. of Mines, Can.* (1909), p. 31; "The Larder Lake District, Ont., and Adjoining Portions of Pontiac County, Que." *Mem. 17, Geol. Surv., Dept. of Mines, Can.*, 1910.

[3] *Amer. Jour. Sci.*, XXIII, 187–92; *Bull. Geol. Soc. Amer.*, XIX, 347–66; *Jour. Geol.*, XVI, 149–58.

[4] The name Abitibi group is here used for those surficial rocks of the older complex occurring in the Timiskaming region, whose stratigraphical and structural relations are as yet unknown.

[5] *Ann. Rep., Can. Geol. Surv.*, X (1897), 96.

[6] *Ann. Rep. Bur. of Mines, Ont.*, XIV (1905), Pt. 3, p. 1289.

pointed out the resemblance of a greywacke conglomerate, occurring in the vicinity of Ramsay Lake, to bowlder clay; and in the same year, W. G. Miller mentioned the possibility of a glacial origin for the conglomerate of the Cobalt series, but also suggested desert conditions of deposition in the following quotation. "The writer is not able to offer a satisfactory explanation for the character of the sediments found in some of these strata. . . . . To account for the undecomposed and angular character of much of the fragmental material, the writer is inclined to the belief that desert conditions prevailed in this region at the time some of the middle Huronian rocks, at least, were formed."[1] R. W. Brock in his report on the Larder Lake District published in 1907,[2] noted some characteristics of the rocks favorable to the glacial hypothesis but concluded that there were still difficulties in the way of its acceptance. He also observed that many of the included fragments had the form of bowlders worn by river sands.

APPLICATION OF CRITERIA

Although the various suggestions in the above quotations all imply a continental origin, none of these writers have pointed out the many characteristics of the series which point to terrestrial conditions of deposition. The great heterogeneity and general absence of complete sorting throughout the greater part of the series, the presence of ripple marks, current marks, cross-bedding, and interformational unconformities, the presence of an ancient soil at the base of the conglomerate in places, the angularity or subangularity of the fragmental material comprising the series, and the great thickness and enormous extent of the conglomerate are features distinctly characteristic of land sediments. It shall therefore be assumed without further discussion that the Cobalt series is of terrestrial origin, the term terrestrial implying deposition on the land in contrast with deposition in the sea or on the seashore.

Continental clastic sediments may be formed by volcanic action or by weathering, creepage, lakes, rivers, winds, or glaciers,

[1] *Ann. Rep. Bur. of Mines, Ont.* (1905), Pt. 2, p. 41.

[2] *Ibid.*, XVI (1907), 212.

the degree of importance and relationship of the latter agencies to one another depending, in part, on climate, and in part, on the topography of the land.[1]

In the following discussion I shall apply some of the criteria which characterize sediments originating in these various ways to the different members of the Cobalt series, and in that way attempt to reach some conclusions as to the climate and conditions of deposition prevailing during this Huronian period.

1. *Pyroclastic origin.*—Owing to the misunderstanding of the relationship of the Huronian of the Timiskaming region to the volcanic rocks of the older complex, the conglomerate of the Cobalt series was at one time thought to be of pyroclastic origin but it is now known that it is almost, if not entirely,[2] composed of material derived from the underlying floor. This mode of origin need not therefore be considered.

2. *Weathering and creepage.*—Since weathering and creepage are closely related processes operating together, for the purpose of this discussion they may be considered as one.

The indefinite contacts which occur at the base of the Cobalt series, in places, indicate that at the time the deposition of the series was initiated, the surface of the ancient complex was covered by a considerable thickness of soil and that this has been preserved so that the basal beds of the conglomerate at these points represent a fossil regolith, developed *in situ* by weathering.

This ancient soil consisted of disaggregated, undecomposed rock fragments, a feature from which some inference may be drawn as to the climate prevailing at the time it was formed. The domination of disintegration over chemical decomposition, on the earth's surface today, is characteristic of regions[3] of youthful topography, is also characteristic of arid climates[4] and to a lesser extent of cold

[1] J. Barrell, *Jour. Geol.*, XVI (1908), 159; A. Penck, *Amer. Jour. Sci.*, XIX (1905), 166.

[2] *Ann. Rep. Bur. of Mines* (1905), Pt. 2, p. 47.

[3] B. Willis, *Jour. Geol.*, I (1893), 477.

[4] E. Pumpelly, *Geol. Soc. Amer.*, XVI (1908), 167; J. Barrell, *Jour. Geol.*, XVI (1908), 167.

or temperate climates,[1] but is not characteristic of warm humid climates.[2] Since this region, at the time the soil was formed, was practically a peneplain, the topographic factor may be eliminated. If it be assumed, therefore, that the variations in the conditions for soil development were the same in pre-Cambrian times as at present, the climate which preceded the deposition of the Cobalt series was either cold and humid, temperate and humid, or arid.

It is possible that owing to the absence of abundant vegetation to supply carbon dioxide to the ground water, or because of differences in the composition of the atmosphere, the relationship of the chemical decay in the soil to climate may have been somewhat different at that early period, but it is doubtful whether this would be of sufficient importance to modify the foregoing conclusion. The abundance of limestone in some of the early pre-Cambrian formations indicates that carbon dioxide was certainly present in the atmosphere at the very beginning of geological time and may have been more abundant than in later periods, for it seems probable that the loss of carbon dioxide from the atmosphere through the formation of limestone and coal beds, since the pre-Cambrian, has been greater than the additions from other sources.

3. *Lacustrine deposition.*—The uniformly stratified argillite, greywacke, arkose, and quartzite which form a considerable part of the Cobalt series were evidently deposited from standing bodies of water and are therefore flood-plain or lacustrine deposits. However, from the general greenish-grey or green color of all these sediments, from the absence as far as has been observed of mud cracks, rain prints, or other evidence of exposure to the air,[3] in even the fine grained argillite, and from the presence of uniformly continuous ripple marks in the quartzite, it seems safe to conclude that these deposits have not been laid down from either flooded rivers or ephemeral lakes, but were deposited from permanent bodies of water which persisted from year to year.

[1] I. C. Russell, *Bull. 52, U.S. Geol. Surv.* (1888), p. 12; G. P. Merrill, *Bull. Geol. Soc. Amer.*, VI (1895), 321–22.

[2] E. W. Hilgard, *Soil* (1906), 398–417.

[3] J. Barrell, *Jour. Geol.*, XVI (1906), 538; J. Walther, *Einleitung in die Geologie* (1897), p. 846.

With regard to the characteristics of these sediments which have a climatic significance, it may be observed from the features mentioned in the previous paragraph, that these, in general, point to humid rather than to arid or semiarid conditions of deposition. Furthermore, bowlders occur in places in the midst[1] of fine grained, stratified greywacke and argillite, a condition which seems to necessitate the presence of floating ice. From this, it may be inferred that the climate of this period was not only humid but cold.

4. *Aeolian deposition.*—Since the greater part of the finer grained material comprising the Cobalt series is uniformly bedded, it is evident that these are subaqueous deposits. Moreover it was pointed out in the previous paragraph that the climate, at the time these materials were laid down, was probably cold and humid. Consequently it may be inferred that aeolian action was never a depositional factor and probably played little or no part in the formation of the series.

5. *Fluviatile deposition.*—The general great heterogeneity of the conglomerate of the Cobalt series, the great variability in the matrix, in the size of the pebbles, and bowlders, and in the rock types represented in the conglomerate, the varying degree of abrasion to which the pebbles and bowlders of the conglomerates have been subjected, the presence of cross-bedding in places are all characteristics commonly pertaining to sediments of a fluviatile origin which have been deposited not far from the source of supply. The conglomerates of the Cobalt series have therefore the essential characteristics of fluviatile deposits.[2]

Notwithstanding, however, the apparent similarity of the conglomerates of the Cobalt series to river deposits, there are some features associated with these which are inconsistent with a fluviatile origin. A considerable part of the bowlders contained in the conglomerate, in places, are 2, 3, or even 8 feet in diameter[3] and are commonly many miles from the nearest occurrence of similar rocks in the older complex. Moreover, the surface upon which

[1] A. B. Coleman, *Jour. Geol.*, XIV (1908), 153.

[2] C. R. Mansfield, *Jour. Geol.*, XV (1907), 550–55.

[3] *Jour. Geol.*, XVI (1908), 151; "Prel. Rep. Gowganda Min. Div.," *Geol. Surv., Dept. of Mines, Can.* (1909), p. 27.

the conglomerate was deposited was one of mature topography, so that the transportation of the large bowlders must have been effected by streams having gentle gradients. In order to explain this difficulty, it has been pointed out[1] that the climate of this Huronian period may have been semiarid and that during floods in regions where such climatic conditions prevail, bowlders of

FIG. 3.—Scratched and faceted pebble from the conglomerate of the Cobalt series, occurring in Boischatel Township, Pontiac County, Quebec—a point about 60 miles northeast of the Cobalt district.

large size may be transported long distances by rivers. But it has already been shown from the character of the greywacke, argillite, arkose, and quartzite associated with the conglomerate, that the climate at the time these rocks were deposited was certainly not arid and was probably humid and cold. Furthermore,

[1] *Ann. Rep. Bur. of Mines, Ont.*, XIV (1905), Pt. 2, p. 47.

the green or greenish-gray color which is everywhere characteristic of the conglomerate is not the color which usually distinguishes more recent fluviatile gravels developed in arid or semiarid regions, so that unless the pre-Cambrian atmosphere was deficient in oxygen this feature also points to humid climatic conditions. Fluviatile conglomerates of the coarse unsorted types which are characteristic of the Cobalt series are limited on the earth's surface at present to regions of youthful topography or arid climates.[1] These factors, usually operating together, have resulted in the building up of immense accumulations of river gravels on piedmont slopes and in interior basins. If it be assumed, therefore, that the conglomerates of the Cobalt series are of fluviatile origin, this conclusion must be reached in the face of the facts that these immense deposits covering a minimum area of 20,000 square miles were built up in a region having a low relief and a pluvial climate, conditions which in every particular are the reverse of those under which similar fluviatile deposits are accumulating on the earth today.

6. *Glacial deposition.*—In a number of papers published within the last few years, A. P. Coleman has advocated the glacial origin of the conglomerates of the Cobalt series, pointing out their striking similarity to the Pleistocene glacial deposits and to similar rocks in other parts of the world to which a glacial origin has been assigned. The principal features emphasized by Coleman are the resemblance of the matrix of the conglomerate to bowlder clay; the enormous extent and great thickness of the conglomerate; the occurrence of immense bowlders at a distance of several miles from the source of supply; the great size, angularity and variety of the pebbles and bowlders of the conglomerate; and, finally, the finding of scratched and "soled" pebbles and bowlders in the conglomerate at Cobalt, Ont.[2]

[1] Medlicott and Blanford, *Geology of India*, p. 397; Huntington, *Carnegie Inst. Exploration in Turkestan*, p. 40; J. Barrell, *Jour. Geol.*, XIV (1906), 330; A. C. Trowbridge, *ibid.*, XIX (1911), 738; E. W. Hilgarde, *Sci.*, N.S., XV (1902), 414; N. S. Shaler, *Bull. Geol. Soc. Amer.*, XII (1907), 271–300; I. C. Russell, *Geol. Mag.*, VI (1886), 289–95; J. L. Rich, *Jour. Sci.*, XVIII (1910), 601–32.

[2] *Amer. Jour. Sci.*, XXIII (1907), 187–92; *Jour. Geol.*, XVI (1908), 149–58; *Bull. Geol. Soc. Amer.*, XIX (1908), 347–466.

As opposed to the glacial hypothesis, it has been maintained that glaciated surfaces should somewhere be found beneath the basal conglomerate instead of the ancient regolith which is commonly present.[1] In reply to this objection, Coleman has pointed out that "near the edge of a glaciated area where the thickness of ice is not great, the ice sheet often moves for many miles over loose material without ever reaching the rock surface beneath," and that this condition existed over thousands of square miles in certain parts of the United States during the Pleistocene continental glacial epoch and also throughout a large part of the area covered by carboniferous bowlder clay in India.[2] It must, furthermore, be recalled that the number of points at which the junction of the Cobalt series and the underlying basement has been examined is not great and that, at some of these, the contact is sharply defined, the conglomerate resting on a smoothly eroded surface. The latter might well be glaciated surfaces, although stream erosion or wave action might no doubt produce a similar effect.

Owing to the firmly cemented character of the conglomerates of the Cobalt series, it is difficult to separate the pebbles and bowlders from their matrix, but during the summer of 1911 an exceptionally favorable locality was found at the eastern end of the Kekeko Hills in Boischatel Township, Que., where Mr. E. M. Burwash, who assisted the writer in the field, succeeded in breaking out some pebbles from the conglomerate which were definitely scratched in several directions (Fig. 3). The conglomerate at this point lies almost horizontal and has been neither mashed nor faulted, so that the scratches cannot be attributed to dynamic action.[3] The pebbles exhibiting the scratches consist of fine grained greenstone and possess the typical rounded corners and faceted faces of glacial stones.

In order to obtain further definite evidence bearing on the glacial origin of the Cobalt series, an attempt was made to count the "soled" pebbles and bowlders in the conglomerates. Only those stones having rounded corners and two or more plane faces,

[1] *Ann. Rep. Bur. of Mines, Ont.*, Pt. 2, p. 58; *Can. Min. Jour.*, XXX, 646–97.

[2] *Jour. Geol.*, XIV (1908), 155; *Can. Min. Jour.*, XXX, 694.

[3] *Ann. Rep. Bur. of Mines, Ont.* (1907), Pt. 2, p. 58.

which, when projected, intersected at a considerable angle, were counted, but since it was not possible to break out the pebbles and bowlders for examination on all sides, the count was made from observation of the outlines exhibited in a given area of rock surface. The results obtained were as follows:

Total Number of Pebbles and Bowlders	Number of Soled Pebbles and Bowlders	Percentage	Locality
205	17	8	Destor Township, Pontiac Co., Que.
210	37	18	Kekeko Hills, Boischatel Township, Pontiac Co., Que.
99	38	38	Labyrinthe River, Dasserat Township, Pontiac Co., Que.
168	54	26	Labyrinthe Hills, Dasserat Township, Pontiac Co., Que.
200	60	30	N. shore Larder Lake, Hearst Township, Nipissing District, Ont.

If it had been possible to break out the pebbles and bowlders and observe them in three dimensions instead of one, the above percentages would certainly be greatly increased.

In the preceding discussion of the glacial hypothesis, attention has been confined to the conglomerates of the series. One of the strongest arguments, however, in favor of Huronian continental glaciation is to be found in a comparison of the series as a whole, to the Pleistocene glacial, fluvioglacial, and postglacial deposits of the same region—for each of these has its exact counterpart in the Cobalt series. At the base of the latter, there is the conglomerate, which, like the Pleistocene glacial drift, is exceedingly variable in thickness, and like the drift is unstratified, in part, resembling till, is rudely sorted and cross-bedded, in part, similar to the fluvioglacial deposits of kames, eskers, and outwash plains, and, in places, passes into unstratified greywacke containing scattered pebbles and bowlders, thus duplicating bowlder clay.[1] Overlying the basal conglomerate, there is the stratified greywacke, argillite, arkose, and quartzite which have their parallel in the Pleistocene postglacial stratified clay and sand of lacustrine

[1] "Prel. Rep. on Gowganda Dist.," *Geol. Surv., Dept. of Mines* (1909), p. 26.

origin.[1] In both of these deposits, bowlders have been found which have been attributed to floating ice.[2] The Cobalt series differs from the Pleistocene deposits of northern Ontario and Quebec in the greater thickness of arkose and quartzite which it contains and in the presence of an upper conglomerate[3] overlying the finer grained members of the series. These conditions, however, would simply imply that the lake which covered the region subsequent to the deposition of the basal conglomerate was of longer duration than that of the Pleistocene, and that following the lacustrine epoch a second continental ice sheet advanced over the region from which an upper conglomerate was laid down. If it be assumed, therefore, that the conglomerates of the Cobalt series are of glacial origin, then there are at least two till sheets present, and the stratified greywacke, argillite, quartzite, and arkose constitute interglacial deposits.

The essential similarity of the greywacke and argillite of the Cobalt series to the postglacial lacustrine clays of the region is shown in the following table of chemical analyses. Column I is an analysis of the argillite and column II that of the stratified clay

	I	II	III	IV	V
SiO_2.........	62.74	52.00	64.81	57.94	61.54
Al_2O_3........	16.94	16.11	17.48	17.92	.....
Fe_2O_3........	5.07	4.69	5.23	5.83	.....
FeO.........	1.59		1.64		
MgO........	3.05	4.10	3.14	4.56	.....
CaO........	1.39	8.26	1.43	9.20	.84
Na_2O.......	6.07	2.76	6.27	3.09	4.73
K_2O.........		1.74		1.95	2.84
H_2O-.......	.36	9.64	.....	.....	.....
HO+.......	3.20	.....	.....	.....	.....
SO_3.........	.....	.09	.....	.10	.....

I. *Ann. Rep. Bur. of Mines, Ont.*, XIV (1905), Pt. 2, p. 48.
II. *Ibid.* (1905), p. 33.
III. I recalculated to a total of 100 omitting water.
IV. II recalculated to a total of 100 omitting water.
V. *Jour. Geol.*, XVIII (1910), 669.

[1] *Ann. Rep. Bur. of Mines, Ont.*, XIV (1905), Pt. 2, p. 33; XVIII (1908), 282, 284; *Sum. Rep. Geol. Surv., Dept. of Mines, Can.*, 1911.

[2] *Jour. Geol.*, XVI (1908), 153; *Ann. Rep. Bur. of Mines, Ont.*, XX (1911), Pt. 1, p. 220.

[3] See table, pp. 124, 125.

occurring at the north end of Lake Timiskaming. In order to make these more nearly comparable, they have been recalculated to a total of 100 omitting the water. In Column V a partial analysis of argillite from Lily Lake in the Gowganda district, is inserted.

It will be observed that in both the argillite and the clay there is an excess of soda over potash, a relationship which is usually reversed in normal sediments of the slate-shale series. The large percentage of lime and magnesia in the postglacial lacustrine deposits is undoubtedly due to the large amounts of Paleozoic limestone which were denuded away by the Pleistocene continental ice sheets and were thus transformed into glacial drift and later redeposited as stratified clay.

CONCLUSION

Having assembled the evidence which might have a bearing on the origin of the Cobalt series, the following conclusions may be cited with regard to the climatic conditions and depositional processes in operation at the time these sediments were laid down: (1) that the series is of terrestrial origin; (2) that the basal portion of the series is in places an ancient regolith; (3) that the stratified greywacke, argillite, quartzite, and arkose are lacustrine deposits; (4) that aeolian deposits are not represented in the series; (5) that the climate of this period was *not* arid or semiarid and was probably cold and humid. (6) With regard to the mode of deposition of the major part of the conglomerate only two hypotheses need be considered. They are either of fluviatile origin or have been deposited from continental ice sheets. From a consideration, however, of the difficulties of transportation involved in the fluviatile hypothesis and that the climate and topography of the region were wholly the reverse of those under which fluviatile deposits of this character are accumulating on the earth today, and on the other hand, the facts that practically every feature of the Cobalt series has its duplicate in the Pleistocene glacial, interglacial, or postglacial deposits of North America, that the pebbles and bowlders of the conglomerates have a characteristically "soled" appearance and that striated pebbles and bowlders have been found in two localities over 60 miles apart, it seems necessary to

conclude that the evidence preponderates in favor of the hypothesis that the conglomerates of the Cobalt series were deposited from pre-Cambrian continental ice sheets.

In the above pages an attempt has been made to apply the criteria which distinguish the various types of continental clastic sediments to the different rock types represented in the Cobalt series and thereby to reach a definite conclusion with regard to their origin. As a result it has been shown that not only has every variation in the series its duplicate in the glacial, interglacial, or postglacial deposits laid down in association with the Pleistocene continental ice sheets of the same region, but that no other known depositional process will so well account for all the many peculiarities and associations of sediments found in the series as the glacial hypothesis. Furthermore, the objection that striated surfaces have not been found beneath the basal conglomerate loses much of its force when it is recalled that only an exceedingly small part of the contact between the Cobalt series and the older complex has been observed, that the underlying surface in some places has been smoothly eroded, and that the presence of the overlying conglomerate at those points generally makes an examination for striae impracticable.

With the progress of detailed geological investigation in regions where pre-Cambrian rocks occur, evidence is accumulating which indicates that the processes at work on the earth's surface today were in operation in the very earliest pre-Cambrian periods. The existence of pre-Cambrian continental ice sheets would therefore be simply another link in the chain of evidence pointing to the uniformity of natural processes from the very earliest time in the earth's history of which we have any knowledge.

THE LATER CENOZOIC HISTORY OF THE WIND RIVER MOUNTAINS, WYOMING

LEWIS G. WESTGATE AND E. B. BRANSON

INTRODUCTION

The Wind River Mountains of West Central Wyoming run from Union Pass on the north, for over one hundred miles southeast to the Sweetwater River near Atlantic City. The range rises from the plains level of 5,000 to 6,000 feet on the east, to a crest line which in a number of places stands over 13,000 feet above the sea. Wind River Peak is 13,500, and Gannett Peak, the highest summit in the range, 13,785 feet above the sea.

The continental divide follows the crest of the range. On the east the drainage is by the Wind River and Platte and its tributaries to the Missouri and the Atlantic. Along the west side, except at the south end where the drainage is by the Sweetwater to the North Platte and the Atlantic, the streams are tributary to the Green River, thence following the Colorado to the Pacific.

Geologically the structure of the range is similar to that of the Big Horns and the Black Hills, and consists of a central axis of crystalline rocks, circled by belts of upturned Paleozoic and Mesozoic rocks, beyond which lie the nearly level Tertiaries. Along most of the east side of the range the conditions in the Black Hills are exactly reproduced, but along much of the south and west sides the Tertiaries overlap the Paleozoics and rest directly against the crystallines. Where all the formations are present each plays a distinctive part in the topography. The crystalline rocks form the central part of the range. The Paleozoics form the main foothills and slopes up to 9,000 or 10,000 feet, while the Mesozoics and Cenozoics underlie the plains. The lowest Mesozoic and highest Paleozoic, the Chugwater Red Beds, which are mainly sandstone, often make prominent ridges, rising 1,000 to 1,500 feet above the neighboring valleys, facing the range, and sometimes separated from it by a conspicuous red valley, worked out on the softer

shales which comprise the lower part of the Chugwater. In the Cretaceous certain sandstones make low ridges, but not at all comparable with those made by the Chugwater. When the Paleozoics are concealed by the Tertiary overlap the topography is simpler, and the rise from plains to mountains more abrupt.

The observations which are recorded in this paper were made in August and September, 1911, on a trip along the base of the range from the headwaters of the Sweetwater River on the west to Bull Lake Creek on the north, with side trips into the range and out onto the plains. The time which could be given to the work was far from sufficient to determine the history of the range fully, and many questions which came up had to be left unanswered. It is thought, however, that the general history of the range, as read in its topography and that of the surrounding plains, has been made out, and that the results are worth making public. We are glad to be able to express our appreciation of the courtesy of Mr. N. H. Brown of Lander, whose maps of Fremont County and of the vicinity of Lander were used in our work. The Fremont quadrangle is the only topographic sheet published by the U.S. Geological Survey which covers any part of the Wind River Mountains. As our field work was to the south of that area, and we were without topographic maps (except those of the Hayden Survey, which were too generalized for our uses), we were obliged to get altitudes by the use of aneroids, and with less opportunity than we would have wished to check such observations by bench marks.

SEDIMENTARY HISTORY: CAMBRIAN TO EARLY TERTIARY

Before the end of Cambrian time a wide transgression of the sea brought conditions of marine sedimentation over the area of the present Wind River Mountains, and from then on to the close of the Mesozoic there was almost continuous sedimentation. If at times deposit was interrupted, as seems probable from the failure to find Silurian and Devonian beds in the series, this did not interfere with the production of an essentially parallel series of sedimentary rocks. The youngest rocks found in the Lander region are the Mancos shale[1] (Colorado), over 6,000 feet, and the Mesa

[1] Woodruff, *Bulletin U.S. Geol. Survey, No. 452*, p. 10.

Verde (Montana), 2,000 feet. At the close of the Cretaceous came the uplift by which the present anticlinal structure of the range was produced. Parallel to the main uplift, and about six to eight miles east from the base of the range, is an anticlinal uplift which brings the Triassic, Jurassic, and Dakota Cretaceous out from under the Mancos shale, producing an interrupted line of hills (especially south of Lander), and forming a longitudinal valley southeast from Lander. This valley is now drained by a number of transverse streams, but this has apparently not always been the case.

Extensive erosion followed the uplift of the region, even before the time of its earliest Tertiary rocks, for we find the Wind River Tertiaries lying on the upturned and eroded edges of the Mesozoic rocks. In early Eocene times, this erosion was replaced, about the base of the mountains, by deposition. The best section of the Tertiary rocks[1] shows along the north face of the Beaver Divide, where the early Eocene (Wind River beds) are overlaid by the Bridger(?) and Uinta, and above an unconformity, by the Oligocene. These Tertiary rocks, largely shales and sandstones, are alluvial deposits laid down by streams from the higher central mountain area. The occurrence in the Beaver Divide Oligocene of a 100-foot gravel layer with bowlders of granite and other crystalline rocks up to a foot in diameter shows not only that there was considerable relief in the mountain region, but that any cover of sedimentaries had been cut through into the crystallines. How long after this the Oligocene deposit continued in the Wind River basin is not known, for the present top of the Oligocene cannot be shown to be the summit of the Tertiary series. Subsequent to Oligocene time came the erosion which ended in the production of the summit peneplain described below. From this point on, the history of the Wind River Mountains is to be read from the land forms and not from the sedimentary rocks.

THE SUMMIT PENEPLAIN

An accordance of summit levels in the central and northern part of the range is believed to be an inheritance from a peneplain which formerly extended throughout the range, and which in its highest

[1] Sinclair and Granger, *Eocene and Oligocene of the Wind River and Big Horn Basins*, Bull. Am. Mus. Nat. Hist., Vol. XXX, Fig. 2 A.

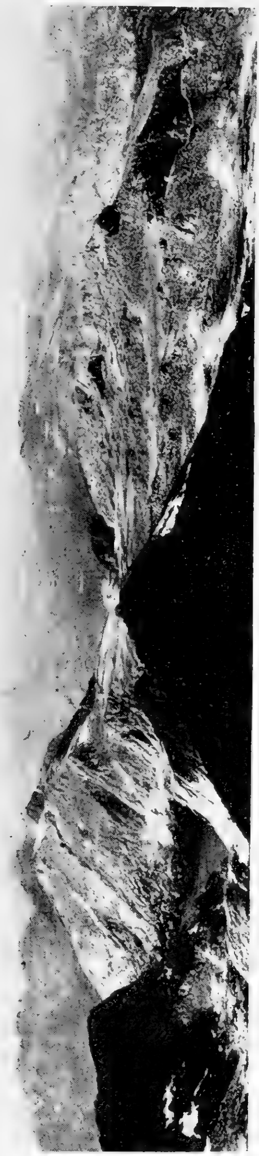

FIG. 1.—View north from Wind River Peak, showing sky line in central part of the range

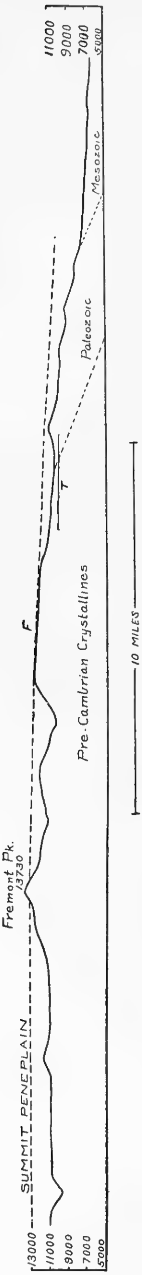

FIG. 2.—Profile across the Wind River Mountains through Fremont Peak. F, flat. T, valley terrace level

remnants now stands about 12,500 feet above sea-level. Looking north from Wind River Peak (Fig. 1) we see the sky line to be composed of rounded summits dropping to the east in an even line, but with occasional points rising sharply above this line. Further north, north and east of Fremont Peak and showing on the Fremont Peak quadrangle, extensive flat or gently rounded areas occur at heights of over 12,000 feet. Such are, the flat east of Indian Pass (Fig. 2, F), Horse Ridge, Goat Flat, the flat along the divide at the north end of the range, and several smaller flats west of the crest. The first two are not strictly level, but rolling, grassed, and rounded upland areas, their higher points rising somewhat above the general flat level.

The whole range was not reduced to the peneplain level. Fremont Peak and the higher points north along the range seem to rise distinctly above the general summit level, and the rate of rise of the ridges or flats which have been named would not carry them to the summit by several hundred feet. We may picture the condition at the close of this epoch as a plain rising along what is now the crest of the range to low rounded hills a few hundred feet in height.

This peneplain is not recognized in the southern part of the range, probably because destroyed by later erosion. From the middle of the range north it is increasingly represented, especially east of the crest. It is preserved only on the crystalline rocks, though the first high escarpment of Paleozoic rocks, the Bighorn limestone, seems to come nearly if not quite to this level. The projection of the plain farther from the crest carries it well above the other Paleozoic scarps. Why it has been more completely destroyed to the south and on the west of the crest, we cannot say.

The remnants of the plain fall into a low arch (Fig. 2), which slopes east from over 12,000 feet along the crest to above 10,000 feet in its last remnants on the edge of the crystallines and the bordering Bighorn limestone, and drops to the northwest along the axis of the range.

The date of the summit peneplain cannot be fixed, from the area studied, more closely than that it is later than the main folding of the range; for it does not extend beyond the Paleozoic rim to any point where later deposits rest upon it. Blackwelder[1] has described a peneplain in the Laramie region of southeastern Wyoming, which makes the summit of the Laramie Mountains at 9,000 feet and cuts the Medicine Bow range at 10,000, with the summits of the latter rising above it as monadnocks. This peneplain is considered to be of post-Eocene age. Rich[2] has described a peneplain in southwestern Wyoming, which had been developed probably by the end of Miocene, while Baker, in a paper read before the Cordilleran section of the Geological Society in 1911, describes the occurrence of a peneplain throughout southwestern Wyoming in the end of the Miocene. Umpleby[3] describes an old erosion surface in West Central Idaho which may prove to be a peneplain and which he considers to be of Eocene age. It is perhaps as much as the facts known at present warrant, to state that the Wind River Mountains had been reduced to a peneplain, except for a few low residuals along the present divide, by mid-Tertiary time.

THE PLAINS AT THE SOUTH END OF THE RANGE

Plain No. 4.—The oldest plain below the summit peneplain is best represented north of Atlantic City, in the summit accordance of a hilly area above which the southern end of the range rises abruptly (Figs. 3, 4, and 5). These summits stand at 8,500 feet farthest from the range, but rise to probably 9,000 feet at its base; and the original plain has been maturely dissected. East of Atlantic City, peaks of Paleozoic limestone rise to the level of this plain at 8,500 feet; and still further east the summit of Sheep

[1] *Journal of Geology*, XVII, 429.

[2] *Ibid.*, XVIII, 601.

[3] *Ibid.*, XX, 139.

Mountain reaches it at about 7,500 feet. The summit of Oregon Buttes, fifteen miles south of Atlantic City may be a remnant of the same plain. They are capped with Tertiary deposits.

This plain was not correlated with any plain-remnants along the range to the north, nor with any valley levels within the range. At the time of its formation, all of the region was reduced to a

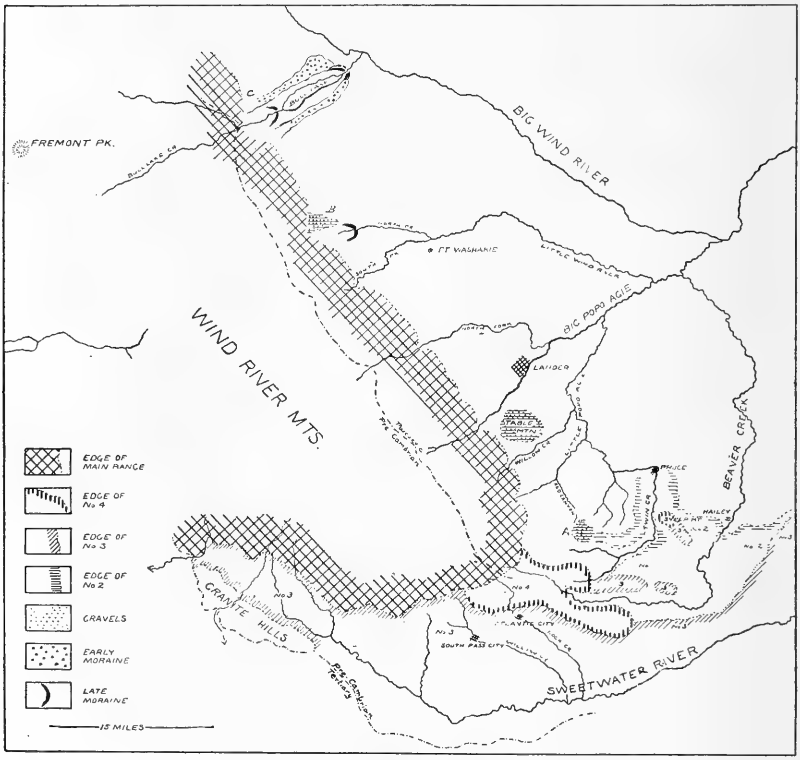

FIG. 3.—Map of the south end of the Wind River mountains, based on a map of Fremont County by N. H. Brown.

peneplain, except the Wind River Range, which rose, at the south, 4,000 feet above the plain level. The date of this plain is post-Oligocene, since it cuts rocks of this date along the Beaver Divide.

Plain No. 3. The Beaver Divide Plain.—Below No. 4 another plain (Figs. 3, 4, and 6) is widely developed about the south end of the Wind River Mountains, and to the east along the divide

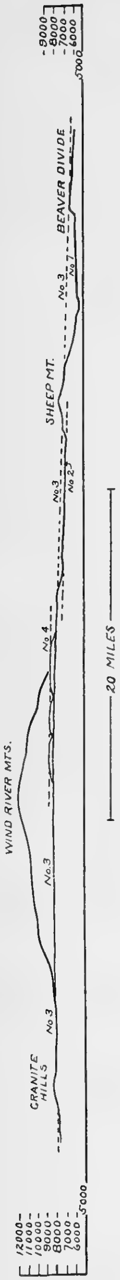

FIG. 4.—Profile of south end of Wind River Mountains

FIG. 5.—Plain No. 4 with the south end of the Wind River Mountains in the distance

between Beaver Creek, and the Sweetwater River. This is plain No. 3, or the Beaver Divide plain.

This plain is best shown west of Atlantic City and South Pass City, where it forms an even plain on the crystalline schists, above which monadnocks (Fig. 6), usually of granite, rise abruptly from a few score to one or two hundred feet. The plain, much cut away, continues west between the Granite Hills and the main range about the headwaters of the Sweetwater, where it cuts both the crystallines

FIG. 6.—View of plain No. 3 and monadnocks, west of South Pass City

and gravels which had earlier been deposited on an irregularly eroded granite surface. This same plain extends east from the south end of the range for over thirty miles along the divide between the Sweetwater River and Beaver Creek cutting in this area practically all the post-crystalline rocks of the region—the inclined Paleozoics and Mesozoics, and the horizontal and consolidated Tertiaries. In a few places residuals of each of these rocks rise above No. 3.

North from Atlantic City, where Nos. 3 and 4 meet, they differ

in level by some 400 feet. The cycle which produced No. 3 passed well beyond maturity, for the slopes joining 3 and 4 are gradual; and broadly opened valleys of No. 3 finger back into the area of No. 4. At the time of its completion the masses rising above its level were, besides the main range, the rolling hills which formed as a whole a dissected terrace at its south end, and occasional knobs along the Beaver Divide to the east.

Today the remnants of No. 3 have a distinct slope away from the range, amounting to about 1° around South Pass City. The plain stands at about 8,000 feet between the Granite Hills and the main range, about 8,000 to 8,200 feet by South Pass City (the higher value at the base of the mountains), 8,200 feet between Beaver Creek and Twin Creek near O'Meara's ranch, and 7,400 feet along the upper Beaver near Atlantic City. Along the Beaver Divide it drops to 6,770 feet ten miles east of Atlantic City, and to 6,600 east of Hailey (twenty-two miles northeast of Atlantic City). The Beaver today is flowing about 400 or 500 feet below the level of this plain.

The drainage on the Beaver Divide plain is unknown. Presumably it was radially away from the range. There is no evidence that the present arrangement of streams held at that time. The slope of the plain may or may not have been what it is today. There seems no way of deciding.

This plain carries gravels on its surface only where it cuts Tertiary rocks and where these rocks contain conglomeratic layers which furnish gravel to the plain.

Plain No. 2. Table Mountain Plain.[1]—Below the Beaver Divide plain, or No. 3, a later plain (Figs. 3 and 4) was very generally developed over the Mesozoic and later rocks of the Wind River region. During this stage the Beaver Divide came into existence and the Wind River and Sweetwater drainage areas became distinct. From this time on the geological history in these two main basins is somewhat different, and the topographical forms are unlike.

The condition of Plain No. 2 in the Sweetwater area is not

[1] Since No. 2 is provisionally correlated with the plain of Table Mountain, west of Lander, it is also called the Table Mountain Plain.

clearly known. On the upper tributaries of the Sweetwater, between the Granite Hills and the main range, No. 3 is post-maturely dissected by a system of valleys which are widely opened on the gravels and are narrower on the granites. This valley system may belong to No. 2. The Sweetwater cuts the crystallines south of the Granite Hills in a narrow valley which has doubtless been cut at a later date. Further east, at South Pass City and at Atlantic City, Willow and Rock Creeks are flowing in narrow valleys, cut below broad shallow valleys which are in turn cut below No. 3. South toward Oregon Buttes, and from the Beaver Divide toward the Sweetwater, the surface drops away to lower levels in such manner as to suggest very strongly that after No. 3 had been formed a later plain was developed to a very advanced stage throughout this part of the Sweetwater basin.

The best development of No. 2, however, is north of the Beaver Divide. Along the Beaver itself large remnants of this plain occur at 6,500 feet, 300 feet below No. 3 as developed on the divide. The only area which stands above No. 2, north of the Beaver and east of the mountains, is the higher part of Sheep Mountain. The plain is well shown along the north side of Beaver Divide as a broad bench sloping to the top of the cañon of the Beaver above Hailey. It forms the flat divide between Beaver and Twin Creeks and continuing from there north makes the high country about Bruce, and either just touches or rises slightly above the hills of folded Red Beds and Cretaceous which run northwest to beyond Lander.

At the south end of the range gravel occurs on No. 2 as scattered bowlders washed from near-by regions rather than as heavy deposits swept out from the central range. For example, in climbing from the Beaver where it bends to the north, to the Beaver Divide, one finds the hill-tops which come up to No. 2 carrying scattered bowlders of angular and subangular shape, frequently five or six inches and occasionally a foot in diameter, and derived from Paleozoic and crystalline rocks. But on the summit of the divide there is found a 100-foot layer of Tertiary conglomerate with bowlders quite like those occurring on the plain below. These bowlders on No. 2 are a thin veneer of local origin, derived from

the Tertiary, and are not to be confused with the Table Mountain gravels to be considered later.

Beyond the fact that the drainage was to the Wind River and the Sweetwater, little is known of the stream courses of the time. The Beaver may have flowed out, as today, south of Sheep Mountain, or, more probably, by a longitudinal stream north toward Lander.

PLAINS-REMNANTS ON THE EAST SIDE OF THE CENTRAL WIND RIVER MOUNTAINS

The Table Mountain Level, or No. 2.—None of the plains which have been described about the south end of the Wind River Range extend continuously north along the east side of the range. There are found, however, along the front of the range, isolated gravel-covered flats, at levels which correspond with those farther south. As careful study as conditions allowed makes it practically certain that these flats correspond to either No. 2 or No. 3 described above; probably to No. 2. The vertical distance between No. 2 and No. 3 is only 300 feet, and in many places No. 2 grades up into No. 3, so that the attempt to carry either plain north and to connect it with the gravel flats is difficult; especially in the absence of topographic maps and under the necessity of carrying the lines by eye from points of view some miles off the front of the range. Provisionally, however, these gravel flats, of which the best known is Table Mountain near Lander, are correlated with Plain No. 2, which has already been called the Table Mountain plain.

The southernmost of these flats is that which occurs (Fig. 3, A) where the Lander–Atlantic City road crosses from the headwaters of Twin Creek to Red Cañon Creek, a tributary of Little Popo-Agie River. Here a terrace (7,100 feet), cut on the Red Beds, is covered by a deposit of gravel to a thickness of 50 to 100 feet as shown on the north slope toward Red Cañon. The bowlders seen over the surface are commonly less than one foot in diameter though some reach a foot, and a few are somewhat larger, but down the north face of the terrace loose bowlders up to six feet in diameter are met with. The bowlders are Paleozoic and crystalline rocks of the foothills and main range, and must have come directly from the range as no Tertiary beds are in position to act as an intermediary

in furnishing the material to the present deposit. The deposit seems to be due to aggradation by the earlier Twin Creek.

A second gravel flat tops Table Mountain south of Lander, south of the Big Popo-Agie, at an elevation of 7,200 to 7,300 feet. A slide on the north side of the Mountain shows 175 feet of gravels resting on a somewhat uneven surface of Chugwater and later beds. In the section the bowlders usually reach a size of one to three feet, but many are over five feet and one was seen ten feet in diameter. The bowlders are well rounded, closely packed, and much weathered and consist of Paleozoics and crystallines. The filling between the bowlders is a sort of granitic sand, which seems to have come from the rotting of the bowlders. From a little distance the deposit appears to be indistinctly stratified. There is no evidence that it is not stream-made, though the size of the bowlders has been thought to indicate ice-action. The bowlders, however, are not larger than those found in arid regions at the head of alluvial fans some distance out from the mouth of the feeding cañons. The slope of Table Mountain is estimated at twenty-five feet per mile away from the mountain. The slope seems too gentle for the accumulation slope of such coarse materials, and the fact that the surface of Table Mountain is not a plain, but is trenched by shallow valleys indicates that it is not original but a cut surface. The Ten Sleep sandstone ridge to the west is cut away to a level corresponding to that of Table Mountain, as if a rather broad valley had here opened out from the range.

A similar deposit of coarse gravels forms a high flat near the range on the north side of the North Fork of Little Wind River (Fig. 3, B), at an elevation of from 7,445 to 7,700 feet. These gravels have a thickness, at the south end of the exposure, of 250 feet, and lie on the inclined Chugwater beds. They consist of well-rounded bowlders up to six feet in diameter, closely packed and thoroughly rotted. Stratification here is distinct and several layers of sand and fine gravel, up to four or five feet in thickness, occur in the deposit, showing that it is water-laid. The surface relations of the deposit are shown in Fig. 7, where *A–B* is the flat under consideration. Its surface is nearly level, and it is cut by *D–E*, a more irregular plain which drops away toward the Wind

River. The slope *A–B* is not an original plain, but was cut after the deposition of the gravels, and antedates the plain *D–E*, which cuts it.

The last terrace deposit of this kind studied is on the north side of Bull Lake Creek (Fig. 3, C), at an elevation of 7,400 feet. No section is shown here, but the deposit lies above and distinct from the moraine of the earlier glacier, which occupied Bull Lake Creek Valley. It is believed to be much earlier than either of the two glaciations of the region.

The meaning of the gravels.—These high level gravels are a largely unsolved problem to us, as are similar deposits to other workers in the Rocky Mountain region. If our correlation is

FIG. 7.—Diagram to show the relation of gravels on No. 2 (*A–B*) to the later plain (*D–E*).

correct, at some time after the up-arching of the summit peneplain which had been developed over the entire region, a peneplain was developed around the mountain on the Mesozoic and younger beds. This is plain No. 2. Low foothills of Paleozoic sandstone and limestone rose above this, and within this Paleozoic rim was the higher mass of the central crystalline area. At this time broad valleys ran back well to the crest of the range. Along Bull Lake Creek, six miles within the range, such flats were seen at 9,800 feet, and they can be seen fingering into the uplands and rising to them with not very steep slopes. This condition was followed by a period of piedmont aggradation, which resulted in the deposit of the gravels widely about the cañon mouths. This aggradation may have been the result of aridity, or of crustal movement. It was followed by the planation which produced the nearly level flats on Table Mountain, Little Wind River, and Bull Lake Creek, which have been described. Subsequent to this period of planation came the long period of terracing which produced No. 1 and lower plains.

Plain No. 1.—After the completion of No. 2, the streams again deepened their valleys and developed widely over the region a series of plains at a lower level. Along the Beaver north from Hailey a flat was formed 8 to 10 miles in width, sloping with the stream and toward the stream from either side. Near the Beaver the remnants now stand 200 feet above the stream. Above the lower Beaver cañon, a little up stream from Hailey, this plain is not shown; nor is it recognized along the Sweetwater.

The valley divide which crosses north of Twin Creek from the main range foothills to Sheep Mountain, is a remnant of No. 2, but from here north the divides between the streams which cross the valley belong to No. 1. On the Little Popo Agie–Willow Creek divide the elevation is 5,575 feet, north of Willow Creek 5,450 feet, and south of Lander 5,480 feet. The remnants of this plain slope from either side toward the axis of the longitudinal valley, indicating that the stream which controlled its formation was a longitudinal stream flowing northwest toward Lander, and that the valley was not drained as it is today, by transverse streams.

North from Lander, between the Popo-Agie and its north fork, a terrace runs far out into the valley and at Milford stands at 5,800 feet. North from this point a series of terraces occurs, below the Table Mountain levels, the highest of which are referred to level No. 1. These terraces stand at 5,730 feet between North Fork and Mill Creek, and at 5,940 feet near the road, north of the North Fork of Little Wind River. The levels rise toward the northwest, along the Wind River, and also toward the mountains.

The cutting of No. 1 was the inauguration of a period of terrace cutting which has continued to the present. New plains have been made by the swinging and deepening streams at successive lower levels, but since this terrace period has been different in the different stream basins, and since in any one basin the terraces run into each other, it was found impossible, in the absence of topographic maps, to study it in any detail. Between the North Fork of the Big Popo-Agie and the Little Wind River these lower terraces often carry large bowlders, up to 3 feet and over in diameter, which seem to have been derived from the erosion of the coarse gravels on plain No. 2, since largely destroyed.

Along the Beaver north from Hailey, No. 1 has been well dissected. During this later terracing Little Popo and Willow Creek have cut back and captured the streams which during the cutting of No. 1 had flowed northwest to Lander. In some cases there has been a recent silting-up of valleys, into which filling the present streams are again cutting. This is the case along the lower Beaver, the Wind River, and Sage Creek. The Little Wind River and the Big Popo are flowing on broad flats, and if silting has been going on they have not commenced to cut again.

GLACIAL HISTORY

The Wind River Mountains support a dozen or more small glaciers, and the summit region shows quite generally an Alpine topography, as a result of cirque growth (Fig. 1). In Pleistocene time glaciers occupied the main valleys, and in some cases extended a number of miles out onto the plains at the base of the range. Glacial features are considered in this paper only for the purpose of dating the terracing which has already been described, and for this purpose the conditions about Bull Lake Creek can best be used (Fig. 8).

Moraines of an earlier and a later period occur; and in each case the ice advanced about ten miles from the foot of the range, almost to the Wind River. The moraines of the later glaciation make concentric ridges about the lower end of Bull Lake and connect with gravel outwash which floors the inner valley (Fig. 8, *A–A*) of Wind River. Since their deposition they have been cut somewhat where Bull Lake Creek passes through them, and along Wind River ten feet of silt has been deposited above the outwash gravels (the river is now cutting into silt and gravels); but in all

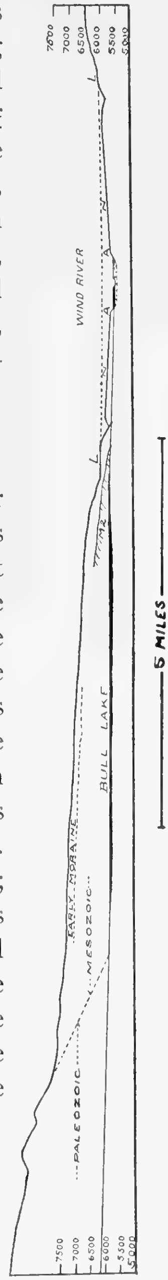

FIG. 8.—Profile along Bull Lake Creek, showing position of the two moraines and of the valley terraces. M2, later moraine

except small details the region has remained otherwise unchanged; so that at the time of the last glacial advance it was essentially as it is today.

The later moraines occur in close association with the present valley of Bull Lake Creek, either as terminal moraines below Bull Lake, or as small recessional moraines up valley. The earlier moraine, however, shows (Fig. 9) a very different relation to the present valley. At the base of the mountains it is 100 to 200 feet thick, with a typical morainic topography, and its mass of bowlders lies on inclined Mesozoic rocks several hundred feet above the floor of the valley. It was laid down in reference to a much shallower valley (probable restoration shown in Fig. 9), and the extension of the drift to the north suggests that near the Wind River

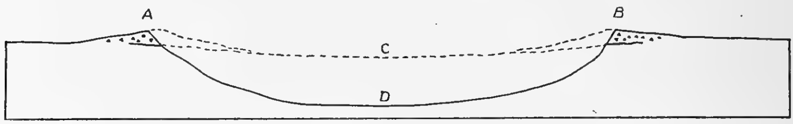

FIG. 9.—Section (diagrammatic) to show the position of the early moraine to the earlier (ABC) and present valley (ABD) of Bull Lake Creek.

the present stream departs from the course of the earlier stream. The cutting of the present Bull Lake Creek, to a depth near the mountain of some 800 feet, is the work of interglacial time.

The earlier drift is known to be older also because of its more weathered and eroded character, and because of its relations to certain terraces. The earlier moraine rests upon a terrace fragment (Fig. 8, L). Fragments of this terrace are found at a corresponding level across the Wind River. This terrace rises toward the range and is overridden by the moraine. It is therefore pre-early glacial. The valley *A–A* existed before the last glacial time, since the outwash gravels of the last ice advance run into it. The cutting of the broad valley below the restored *L–L*, which is floored by the terrace *N–N*, is also the work of interglacial time, and was done at the same time that Bull Lake Creek was deepening its earlier valley. The broad terrace *L–L*, reaching back toward the range, is one of the later terraces of the Wind River region, either No. 1 or later, but it was cut before the earlier glaciation. It

follows that the long period of terracing which has been described, in which plains 4, 3, 2, and 1 were successively formed, is all to be placed before the time of the earlier glaciation. It may be that there were still earlier glaciations in the Wind River Range but if there were they have not been recognized, and for the present practically all of the higher terraces may be assigned to the Tertiary.

VARIATIONS OF CERTAIN ADIRONDACK BASIC INTRUSIVES[1]

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INTRODUCTION

The basic intrusives—gabbros and diabases—discussed in this paper are wholly confined to the North Creek (Warren Co.) New York quadrangle, a detailed geologic map of which will soon appear as a publication of the New York State Museum. The region, though well within the Adirondack area, has afforded an unusual opportunity for detailed field work because of the numerous roads and trails and the large number of excellent exposures as compared with the Adirondacks in general. The gabbros occur almost always as small stocks or bosses, while the diabase always occurs as true dikes. In all, 61 gabbro masses and 11 diabase dikes have been mapped within the quadrangle. Among the gabbros there are many remarkable variations of primary and secondary origin. It is the chief purpose of this paper to describe and attempt to explain the primary variations, though certain secondary features will also be briefly discussed. The writer is greatly indebted to Professors J. F. Kemp, H. P. Cushing, and C. H. Smyth for their able papers dealing with Adirondack basic intrusives, but, so far as the writer is aware, little or no attention has been given to an explanation of the primary variations of the gabbro.

ROCKS OF THE REGION

The rocks of the North Creek quadrangle are all of pre-Cambrian age, and these given in their relative order of ages comprise the Grenville sedimentary series of various gneisses, quartzite, and crystalline limestone; syenite and granite; gabbro; pegmatite; and diabase.

The Grenville strata are all highly metamorphosed, with limestone unusually prominent in this portion of the Adirondacks.

[1] Published by permission of Dr. J. M. Clarke, State Geologist of New York.

The syenite and granite break through the Grenville in batholithic masses of greater or lesser extent. These rocks, which are always foliated, vary from basic syenite through quartz syenite and granite to granite porphyry, and all are differentiation products from the same great cooling magma. About two-thirds of the area of the quadrangle is occupied by these rocks. Sometimes they are so closely involved with the Grenville as to preclude the possibility of separate mapping.

The gabbro, which exists under many facies, is clearly intrusive into the Grenville and syenite-granite series. It is generally more or less metamorphosed, especially along its borders where amphibolite is often developed. It occurs in numerous small masses.

Pegmatite dikes show a very close association with the gabbro, it being quite the rule to find such coarse grained dikes often of very respectable size cutting the gabbros and frequently sending small tongues into the latter rock.

Diabase occurs in small dikes, and in contrast with the gabbro, it is remarkably uniform in texture and composition. The writer has observed the diabase cutting the pegmatites and, in one case, the gabbro.

The accompanying geologic map gives a fair idea of the relations of the various rocks of the region under discussion.

THE GABBRO AND ITS DERIVATIVES

MODE OF OCCURRENCE

The gabbro and its derivatives nearly always occur in the form of small stocks or bosses rather than as true dikes, the length ranging from 30 or 40 feet to about a mile, and with widths up to $\frac{3}{4}$ of a mile. The ground plan as represented on the geological map is almost invariably elliptical, though sometimes approaching the circular. When the contact with the country rock is carefully traced out it is commonly found to be sharp and shows smooth or flowing outlines against the country rock. These features are pretty well shown on the accompanying map.

In only two or three cases do the gabbro masses approach the true dike-like form, and in each of these fine grained tongues were found to extend into the surrounding rock. A good example is

the stock or dike $1\frac{1}{3}$ miles southeast of Chestertown which has several such tongues, one of them from 1 to 6 inches wide clearly cutting the granite porphyry for 30 feet. However, it is a striking fact, that, in spite of many excellent contacts which were

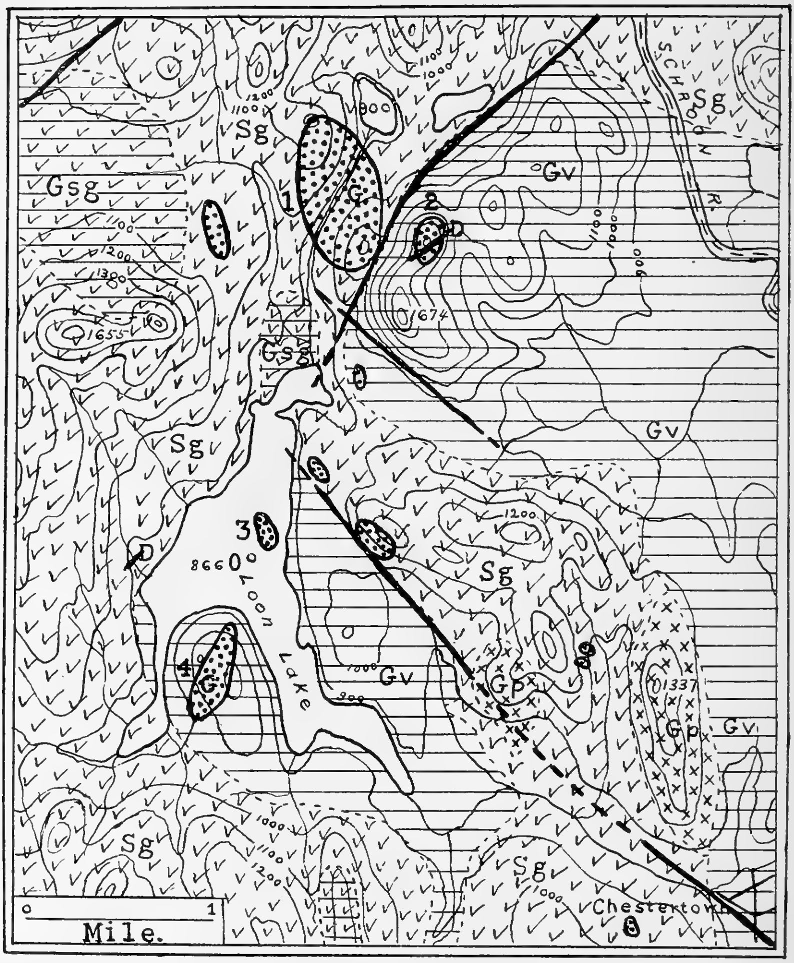

FIG. 1.—Geologic map of part of the North Creek, New York, quadrangle, showing the relation of the gabbro stocks to the other pre-Cambrian rocks.

Gv. = Grenville series; Sg. = Syenite and granite gneisses; Gsg. = Grenville-syenite-granite mixed gneisses; G. = Gabbro; and D. = Diabase. Heavy black lines = faults. Contour interval = 100 feet.

observed, such dike tongues are so rare. As Harker says:[1] "Although most of the bodies of granite and other plutonic rocks which have been loosely described as bosses, and so rendered in ideal sections, are doubtless of laccolithic or other stratiform shape; some, not of the largest dimensions, appear to have a plug-like form, with more or less vertical boundaries." The North Creek bosses are certainly of this plug-like or pipe-like form as shown by the very character of their eroded cross-sections and also by the vertical contacts with the country rock. Among the many fine contacts which came under the writer's observation, not a single exception to the rule of vertical or practically vertical contacts was noted.

In most cases the long axes of the stocks lie parallel to the foliation of the inclosing rock, though there are some notable exceptions. It would therefore seem that the molten intrusives generally followed the lines of least resistance but, even in these cases, the broad ends of the stocks cut sharply across the foliation bands, sometimes for a distance of several hundred yards. Such a phenomenon is well exhibited at the south end of the large stock (see accompanying map) where a big quarry has been opened up along the contact.

The gabbro stocks are not at all uniformly distributed over the area of the quadrangle, the largest number being confined to a nearly north-south belt with a width of from 3 to 5 miles and extending through the middle of the quadrangle. This belt roughly corresponds to the general strike of the foliation. A secondary belt, about 1 mile wide and 5 miles long near the middle eastern boundary of the sheet, contains a dozen small stocks. With a single small exception the whole western side of the quadrangle is devoid of gabbro masses. In the northeastern portion a few stocks occur, but they may really belong to some other belt not yet mapped. Thus we see that the gabbro intrusions were limited to pretty well defined areas or belts.

Among these gabbro stocks four types of occurrence are especially noteworthy as follows: (1) the normal, dark, basic gabbro with diabasic texture, and usually homogeneous throughout;

[1] *Natural History of Igneous Rocks* (1909), p. 86.

(2) gabbro chiefly of the normal type but with irregular patches or masses of lighter colored rocks of syenitic or dioritic make-up, these patches blending with the normal gabbro; (3) the whole stock made up of lighter colored, more acidic rock; and (4) any one of the above types with blocks or inclusions of the country rock. These four types are all primary variations. Examples of the last three types will be given later.

MEGASCOPIC FEATURES

The gabbro and its derivatives present a truly remarkable number of facies or varieties clearly visible to the naked eye and these will now be briefly described.

The coarseness of grain varies from the merest fraction of a millimeter to fully an inch (e.g., stock No. 4 of accompanying map). The fine grained portions are confined to the borders of the stocks or the few branching tongues, and were caused by the more rapid chilling of the rock in those positions. However, even the finest grained rocks are holocrystalline. As a rule the coarseness of grain increases toward the interior of the masses, though often medium to coarse grained rocks extend to the very contact. The typical or prevailing gabbro shows a medium grain; that is, the grains are from 1 to 5 mm. across.

The texture varies from coarse to medium to fine grained granitoid, to medium to coarse grained diabasic (ophitic). The gabbro from stock No. 4 is an excellent example of diabase texture in which the feldspar laths attain a length of an inch or more. The typical gabbro always exhibits the diabasic texture.

In color the gabbro and its derivatives range from nearly black through dark to light gray, the darker varieties, in many cases, showing a slight reddish tinge due to the presence of garnets. The gray rocks all belong to the more acidic—dioritic and syenitic—facies below described. In one case a greenish-gray color was noted. The very dark color of the typical gabbro is due to the fact that the feldspars are so charged with tiny black inclusions.

In the typical gabbros the minerals commonly recognizable with the naked eye or hand lens are plagioclase, pyroxene, horn-

blende, garnet, biotite, and ilmenite, while in addition to these orthoclase and quartz may often be seen in the more acidic phases.

Except for the pretty common presence of highly gneissoid to even schistose amphibolite borders, the stocks of typical gabbro are practically devoid of gneissoid structure. Some of the lighter colored, more acidic phases; however, show fairly well developed foliation.

It is important to note that many of the above described variations may be found within a single stock as, e.g., No. 1. The following statements from Smyth's description[1] of a similar western Adirondack gabbro fittingly apply here:

> These (primary) changes in character take place very suddenly, and the different phases are most irregularly distributed, seeming to conform to no law. . . . . These primary variations in the rock suffice to give considerable diversity to different portions within a limited area, but this diversity is greatly intensified by certain secondary modifications of structure and composition. As a result of the combined effect of primary and secondary variations, it would be easy to collect, within an area of a few square rods, a half dozen or more specimens whose appearance even in thin-section would scarcely suggest that they had any connection with one another.

Cushing says[2] of the Adirondack gabbros in general that they show much variation, both primary and secondary, from place to place. Both of these investigators proceed to discuss the secondary variations and their causes but, so far as the writer is aware, little or no attention has been given to the causes of the primary variations, which is the chief object of this paper.

MICROSCOPIC FEATURES

Mineralogical composition.—The following table will serve to show the great range in mineralogical composition of the gabbro and its derivatives. The figures refer to percentages by volume and are meant to be close approximations only.

Perhaps the most striking feature brought out by this table is the range of rock types, through many intermediate phases, from a very basic olivine norite to quartz-hornblende syenite. Thus, No. 1 is an olivine norite; Nos. 2, 3, 4, 6, 7, and 9 are

[1] *Amer. Jour. Sci.* (April, 1896), pp. 273–74.

[2] *N.Y. State Mus. Bull.*, 95, p. 328.

TABLE I

MINERALOGICAL COMPOSITION OF THE GABBRO AND ITS DERIVATIVES

	Slide No.	Ortho-clase	Plagio-clase	Horn-blende	Hyper-sthene	Augite	Dial-lage	Ilmenite	Pyrite	Biotite	Garnet	Quartz	Zoisite	Zircon	Apatite	Olivine	Titanite
1.......	45	..	Lab. 50	..	15	..	..	3	..	9	8	..	..	..	..	15	..
2.......	6	..	Lab. 50	8	17	..	7	1	little	8	8	..	..	..	..	..	..
3.......	2	4.5	Ol.-Lab. 38	27	12.5	3	..	2.5	1	7	3.5	..	..	..	little	..	..
4.......	46	15	Lab. 30	10	15	..	..	5	..	5	20	..	..	..	..	..	..
5.......	42	10	Ol.-Lab. 40	25	..	..	23	little	little	1	little	..	..	..	..	..	..
6.......	47	10	Ol.-Lab. 30	25	20	..	10	1	..	2	2	..	..	..	..	..	..
7.......	1	5	Ol.-Lab. 40	16	25	..	..	1	..	5	8	..	..	..	..	..	..
8.......	60	20	Ol.-Lab. 40	10	14	..	..	1	1	2	10	1	1	..	..	..	..
9.......	5	5	Ol.-Lab. 45	14	20	..	..	2	1	6	2	..	..	..	..	..	..
10.......	49	32	Ol.-Lab. 10	45	..	..	..	2	little	6	5	..	..	little	..	..	..
11.......	3	32	Ol.-And. 20	25	..	..	..	5	..	5	..	10	1	..	little	..	little
12.......	4	15	Ol.-Lab. 57	15	..	..	..	2	1	10	..	..	..	little	..	..	..
13.......	44	50	Ol.-Lab. 15	20	..	8	2	little	little	..	1	2	..	little	little	..	..
14.......	43	45	Ol.-And. 15	28	..	2	..	1	little	..	..	8	..	..	little	..	..

hornblende norites; No. 5 is a hornblende gabbro; No. 8 is a gabbro-diorite; Nos. 10, 13, and 14 are hornblende syenites; No. 11 is a monzonite; and No. 12 is a diorite. The large number of minerals—16 in all—is also notable. Also it is important to note that, in the above table, Nos. 3 and 4, 7 and 8, 9 and 10, and 11 and 12, respectively, come from single stocks.

The predominating mineral is feldspar, which ranges from labradorite alone in some rocks through all stages, to those rocks which are rich in the more acid plagioclases or orthoclase.

Hornblende, generally in considerable amount, occurs in all but one (No. 1) of the rocks. Sometimes it makes up a fourth or more of the whole rock. Much of the hornblende in the more basic rocks, at least, is of secondary origin and forms corrosion rims (below described) around other minerals. Its color varies from green to brown. In one slide many examples of the transition from pyroxene to hornblende are perfectly shown.

Hypersthene, with a single exception (No. 5), is an important constituent of all the more basic types. It is almost always highly granulated and with pleochroism from greenish-gray to pale reddish-brown.

Augite and diallage of greenish-gray color, and with good cleavage, are only occasionally present and rarely as important constituents.

Ilmenite is invariably present in amounts up to 5 per cent, and often shows transition to leucoxene.

Pyrite in small amount seldom fails.

Biotite and garnet of the usual sort, though mostly in tiny flakes or grains, are present in moderate quantity in all but certain of the more acidic facies. The unusually high percentage of garnet in No. 4 is a fine grained border phase of a stock.

Quartz, in small irregular shaped grains, is wholly confined to the acidic types.

Zoisite, in small stout prisms, sometimes makes up about 1 per cent of the rock.

Zircon and apatite, in very small quantities, are wholly confined to the acidic facies. The absence of the apatite from the typical gabbros is especially noteworthy.

Olivine was noted in but one case (No. 1) and this in the only rock from which hornblende is missing.

Titanite in a few small grains was noted in No. 11.

Reaction or corrosion rims.—Reaction or corrosion rims, which are well known in many basic rocks, are exhibited in a truly remarkable manner in the North Creek region gabbros. In the examples most often described, the core is olivine, but in the gabbros here considered the writer has observed cores of olivine, hypersthene, magnetite, augite, and diallage with from one to five distinct, successive rims surrounding the cores. Professor Kemp has described[1] and figured a number of interesting examples of reaction rims observed in certain gabbros of the eastern Adirondacks.

The following nine types of reaction rims comprise most of those noted by the writer in the North Creek gabbros:

1. Ilmenite surrounded by hornblende.
2. Diallage surrounded by hornblende.
3. Augite surrounded by hornblende.
4. Hypersthene surrounded by garnet.
5. Hypersthene surrounded by successive zones of biotite and hornblende.
6. Olivine with successive zones of hypersthene, hornblende, and garnet.
7. Olivine with successive zones of hypersthene, biotite, and garnet.
8. Hypersthene with successive zones of biotite, feldspar, and garnet.
9. Ilmenite with successive zones of biotite, hornblende, garnet, and biotite.

In nearly all cases the material immediately inclosing the rims is feldspar which, in a sense, adds another zone to each of the above. No. 6 is like one of those described by Kemp. No. 9 is a remarkable example and, because of its additional outer rim of biotite, is even more interesting than a case described by Lacroix.[2] Some of the others may be new examples. The material of each rim appears to be highly granulated or at least made up of numerous small grains. It seems certain that where hypersthene

[1] *Geol. Soc. Amer. Bull.*, V (1894), 218–21.

[2] *Bull. Soc. Min. Fr.*, XII (1889), 232.

FIG. 2

FIG. 3

FIGS. 2. and 3.—Photomicrographs of thin-sections of gabbro from stock No. 4 (see accompanying map). Each magnified 15 diameters.

In the upper figure the large central mineral is olivine completely surrounded by successive rims of hypersthene, biotite (narrow and dark), and garnet. Surrounding all are broad laths of labradorite.

In the lower figure the large, black, central mineral is ilmenite followed by successive rims of biotite, hornblende, garnet, and biotite. The second and third—biotite and hornblende—rims are not separable in the photograph. Surrounding all are labradorite crystals.

envelopes olivine, the former has secondarily developed from the latter. The olivine cores are of very irregular shapes and in all sizes. Where hypersthene forms the core it is probable that all of the original olivine has been altered to hypersthene. The common occurrence of hornblende rims around pyroxene strongly suggests the derivation of the former from the latter. Garnet is almost invariably in contact with feldspar, which suggests the partial formation, at least, of the garnet from the feldspar.

CHEMICAL COMPOSITION, NORM, AND MODE

Excellent exposures of what is regarded as very typical gabbro occur in the railroad cut $1\frac{1}{4}$ miles south of The Glen. This rock has been chemically analyzed for the writer by Professor E. W. Morley. The following table shows the chemical composition, norm, and mode, the last having been determined from thin-sections.

TABLE II

Chem. Comp.		Norm		Mode	
SiO_2	46.40	Orth.	6.67	Plagioclase	32.72
Al_2O_3	14.17	Alb	22.53	Orthoclase	3.77
Fe_2O_3	2.03	Anor	23.35	Hornblende	27.92
FeO	13.12	NaCl	.82	Hypersthene	14.30
MgO	4.94	Ilm	5.78	Biotite	7.09
CaO	9.65	Mag	3.02	Augite	3.29
Na_2O	3.14	Pyr	.24	Garnet	4.30
K_2O	1.12	Apat	2.02	Ilmenite	4.17
H_2O+	.02	Diop	17.53	Pyrite	2.08
H_2O-	.25	Hyper	8.02	Apatite	.36
TiO_2	3.03	Oliv	9.32		
P_2O_5	.80	H_2O+ZrO_2	.32		
Cl	.15				
MnO	.44				
S	.14				
BaO	.18				
SrO	.10				
F	.04				
ZrO_2	.05				
Total	99.77				

Class III	Order 5	Rang 3	Subrang 4
Salfemane	Gallare	Camptonase	Camptonose

Under the old qualitative system the rock is a hornblende norite, while according to the quantitative system it is a hornblende-camptonose.

In thin-section the plagioclase is seen to range from oligoclase to labradorite, and the analysis and mode show that the average composition is that of a basic andesine.

The high TiO_2 of the analysis shows either ilmenite or very titaniferous magnetite, the ilmenite being far more probable because of the difficulty of otherwise accounting for such a low content of Fe_2O_3.

THE DIABASE

MODE OF OCCURRENCE AND DISTRIBUTION

In striking contrast with the neighboring gabbro, the diabase invariably occurs in typical dikes which have clearly broken through narrow fissures in the country rock. They vary in length from 20 or 30 feet to 200 yards, and in width from $5\frac{1}{2}$ inches to 40 feet.

The chief features of occurrence are brought out in the following description of the largest dike of the region which lies at the western base of Heath Mountain or 3 miles west-northwest of Warrensburg. This dike has a maximum width of 40 feet and a length of 200 yards. It is fine to medium grained toward the interior and very fine grained along the borders. It breaks through both Grenville and granite gneisses and the contacts are everywhere perfectly sharp, there being no evidence whatever of contact metamorphism. A number of small tongues, from one inch to three or four feet wide, branch off the large dike and extend as much as 25 or 30 feet into the country rock. One of these branches cuts a pegmatite dike and another cuts Grenville limestone. This large dike strikes across the foliation almost at right angles.

One and one-half miles southeast of Johnsburg a diabase dike, $2\frac{1}{2}$ feet wide and 60 feet long, cuts Grenville quartzite parallel to the foliation. All of this rock is fine grained but exceptionally so at the contacts, and on one side an inch wide zone of basaltic glass or obsidian is perfectly developed with some very small tongues of glass extending into the country rock.

Cutting gabbro stock No. 2 (accompanying map) there is a typical diabase dike 4 feet wide, with fine grained borders, and with very sharp contacts against the gabbro.

In all 11 diabase dikes were found, these being well scattered over the quadrangle. Most of them cut across the foliation of the country rock at high angles, thus differing from the gabbros, and they probably have been forced up along joint planes. In 9 of the 11 occurrences the dikes strike northeast and southwest which is quite the rule for such dikes in the eastern Adirondacks. So far as can be determined, these dikes all come up vertically through the country rock.

MEGASCOPIC AND MICROSCOPIC FEATURES

The diabase is a very dark bluish-gray to almost black rock which, in all exposures, is hard and fresh except for the immediate surface which is often weathered to reddish-brown.

The granularity and texture vary from glassy to very fine grained to medium grained diabasic, the finer grained rock being wholly confined to the borders and the diabasic texture nearly always being just visible to the naked eye in the typical medium grained rock. Except for the above named differences the diabase shows no facies whatever visible to the naked eye, and this again is in marked contrast with the gabbros.

The diabase is wholly devoid of any metamorphism and inclusions of country rock are never found. The only minerals recognizable by the naked eye are the tiny feldspar laths and an occasional pyrite speck.

The whole range in mineralogical composition is brought out in the following table. The figures refer to percentages by volume and are meant to be close approximations only.

The remarkable similarity in composition and the small number of minerals represented stand out in marked contrast against the gabbro and its facies. Nos. 1, 2, and 3 are typical holocrystalline diabases from widely separated dikes. Nos. 4 and 5 represent finer grained or border phases and have more or less glassy groundmass. No. 5 presents a striking appearance under the microscope because the feldspar crystals which are incipient and almost indeterminate tend toward sheaf-like bundles.

No. 1 of Table III, which may be regarded as typical of all the diabases, is from the large dike (above described) at the base of Heath Mountain. The fine to medium grained rock shows an

excellent diabasic texture visible even to the naked eye. Judging by the extinction angles, the broad laths of somewhat decomposed plagioclase range from andesine to labradorite in composition. Pale reddish-brown augite, in stout prisms, shows a very faint pleochroism. It exhibits good cleavage and sometimes good crystal boundaries. The biotite is much changed to chlorite and stained with black iron oxide. The magnetite often shows transition to leucoxene. Apatite occurs in tiny needles, and pyrite and quartz in small irregular grains, the latter probably being of secondary origin.

TABLE III

MINERALOGICAL COMPOSITION OF THE DIABASE

	Slide No.	Andesine to Labradorite	Augite	Biotite	Ilmenite	Pyrite	Glassy Groundmass	Quartz	Apatite
1	8	47	25	22.5	4	½	..	little	little
2	48	55	37 mostly chlorite		6	little	..	2	little
3	7	55	40 mostly chlorite		5	..	..	little	little
4	10	5	5	..	many specks	..	85	..	..
5	9	55	14	..	5	little	25	1	..

CHEMICAL COMPOSITION, NORM, AND MODE

The diabase from the dike at the western base of Heath Mountain has been chemically analyzed for the writer by Professor E. W. Morley. The following table (p. 174) shows the chemical composition, norm, and mode, the last having been determined from thin-sections.

Thus, according to the old qualitative classification, the rock is a biotite-diabase, while under the new quantitative chemical classification it is a biotite-camptonose.

The amounts of SiO_2, Al_2O_3, and CaO in the analysis strongly bear out the determination of the plagioclase as ranging from andesine to labradorite.

Such a high content of FeO in the analysis makes it certain that the biotite is rich in ferrous iron, since there is not enough ilmenite and augite to account for so much FeO.

The sulphur appears too low in the analysis as judged by the amount of pyrite visible even to the naked eye.

The high TiO_2 shows either ilmenite or that the magnetite is decidedly titaniferous (most likely the former), though a little of the TiO_2 may be in the biotite.

TABLE IV

Chem. Comp.		Norm		Mode	
SiO_2	50.57	Qtz.	2.04	Plagioclase	40.78
Al_2O_3	13.58	Orth	11.12	Augite	27.20
Fe_2O_3	3.26	Alb	24.10	Biotite	23.59
FeO	10.09	Anor	18.63	Ilmenite	6.56
MgO	4.98	NaCl	.12	Pyrite	1.13
CaO	7.67	Mag.	4.64	Quartz	.52
Na_2O	2.92	Ilm	5.02	Apatite	.19
K_2O	1.89	Apat	.67		
H_2O+	.16	Fluor	.16		
H_2O-	.94	Diop	14.44		
TiO_2	2.68	Hyper	17.41		
P_2O_5	.28	H_2O+S	1.13		
Cl	.09				
F	.09				
MnO	.36				
BaO	.09				
SrO	.10				
S	.03				
Total	99.78				

Class III	Order 5	Rang 3	Subrang
Salfemane	Gallare	Camptonase	Camptonose

It is important to note that the typical gabbro and diabase are almost exactly the same in chemical composition (both being camptonose) except for somewhat higher silica and lower lime in the diabase, this difference probably being due to the slightly more acid character of the plagioclase in the diabase. Thus, these two rocks have quite certainly been derived from the same basic source of supply, though at different times.

CAUSE OF THE PRIMARY VARIATIONS OF THE GABBRO

APPLICATION OF DALY'S MAGMATIC STOPING HYPOTHESIS

What has caused the remarkable primary variations of the gabbros? The writer believes there is strong evidence favoring the application, to a greater or lesser extent, of Daly's magmatic stoping and assimilation hypothesis to the solution of this problem.

It is the present purpose to state only the fundamental principles of this hypothesis, the reader being referred to Daly's original papers[1] for details. The essential points, according to Daly, are:

1. "Each acid, batholithic magma has reached its present position in the earth's crust largely through the successive engulfment of blocks broken out of the roof and walls of the batholith."

2. "The sunken blocks must be dissolved in the depths of the original fluid, magmatic body, with the formation of a 'syntectic,' secondary magma."

3. The period of most active intrusion, accompanied by stoping and abyssal assimilation, is when the magma is thoroughly molten.

4. When the magma or stock becomes very viscous, the blocks (xenoliths) will neither sink nor become assimilated.

In all of Daly's papers it would seem that his hypothesis is generally meant to account for only large and more acidic intrusive bodies than the gabbro stocks here considered. However, there appears to be no reason why the essential principles of the hypothesis should not be applicable to these smaller and generally more basic stocks.

It should be distinctly understood that the writer does not believe Daly's hypothesis to involve the only processes to account for the type of occurrence and primary variations of these gabbro stocks, but rather the observed facts warrant his belief that magmatic stoping and assimilation have been important processes. Other processes, such as marginal assimilation, or in the cases of certain smaller and more dike-like masses, simple pushing aside (displacement) of the country rock, may well enough have operated.

SIGNIFICANCE OF THE MODE OF OCCURRENCE

We have shown that the gabbro stocks are of the plug-like or pipe-like form with practically vertical boundaries. Now, as Harker says:[2]

> An intrusive working its way up through solid rocks by "overhead stoping" must if this action be sufficiently continued, acquire something of the vertical

[1] *Amer. Jour. Sci.*, XV (1903), 269–98; *ibid.*, XVI (1903), 107–26; *ibid.*, XXVI (1908), 17–50.

[2] *Natural History of Igneous Rocks*, p. 86.

cylindrical form which seems to be implied in the term boss (or stock). . . . . . The space which they (bosses or stocks) occupy can scarcely have been provided by the thrusting aside of the contiguous rocks, assisted by some contraction of the latter in metamorphism. They appear, as Barrois says of the granite of Rostrenan in Brittany, to have penetrated the solid rocks by cutting a way through them like a punch, not by thrusting them aside like a wedge. In such cases we may suppose that "stoping" has played an important part.

Daly, speaking of granite stocks and batholiths, says:[1]

Most, if not all, of these bodies in their accessible portions have replaced nearly equivalent volumes of their respective country rocks. They are generally cross-cutting bodies. . . . . Where erosion has been profound, the ground plan section of the typical stock or batholith is seen to be elliptical. . . . . Both in ground plan and in vertical sections the contact surface is relatively smooth. Apophysal offshoots do interrupt the wall-rock, but the main contact lines as mapped on ordinary geological maps are characteristically flowing lines. Large scale, angular projections of country rock into well uncovered batholith are comparatively rare. Such smoothness of main contact surfaces is that which is to be expected on the stoping hypothesis.

These statements by Harker and Daly are precisely descriptive of the mode of occurrence of the typical basic stocks of the North Creek region. Stock No. 1 (see map) already described is a fine example. This rock was certainly not intruded by displacing or simply pushing aside the country rock, but rather it was a process of replacement. Thus the mode of occurrence of the North Creek stocks furnishes strong evidence in favor of magmatic stoping as an important factor in the intrusive process.

SIGNIFICANCE OF THE INCLUSIONS

A good proportion of the stocks contain inclusions of country rock. Among many examples are the following: $1\frac{1}{4}$ miles north-northeast of The Glen; 1 mile south-southeast of The Glen; $1\frac{1}{3}$ miles south of South Horicon; and $1\frac{1}{3}$ miles northeast of Pottersville. These inclusions, which are seldom more than a few feet long, are usually angular and irregularly arranged in the matrix. It is quite the rule that the dark colored minerals of the gabbro are arranged with long axes parallel to the long axes of the inclusions, this probably having been due to a sort of flow structure

[1] *Amer. Jour. Sci.*, XXVI (1908), 20.

which was developed around the inclusions during their movement through the magma and just before its solidification. The very presence of the inclusions or xenoliths proves that the process of stoping or rifting off of blocks from the chamber vault or sides actually did take place to a certain extent at least, and this when the magma had cooled to a highly viscous condition and hence had comparatively little power to stope and too low a temperature to assimilate the blocks. Thus the occurrence of these xenoliths is quite in harmony with Daly's hypothesis.

SIGNIFICANCE OF THE MORE ACIDIC MASSES WITHIN THE STOCKS

As already mentioned, lighter colored, more acidic patches or masses sometimes occur within the gabbro stocks. These patches lack the diabasic texture of the inclosing gabbro and, instead of being in sharp contact with the gabbro, they rapidly grade into it. A good example is the stock 1¼ miles north-northeast of The Glen and represented by Nos. 7 and 8 in Table I, and another is stock No. 1 (see map) and represented by Nos. 9 and 10 in Table I.

Harker[1] admits the probability of stoping, but sees "no evidence of concomitant assimilation," and Iddings[2] says: "Evidences of absorption by the igneous magma of material from adjoining rocks are very slight. . . . . It commonly happens that blocks, or fragments of rocks, are inclosed in molten magma without exhibiting evidences of solutional reaction between the magma and inclosed rocks. . . . . Few statements as to signs of solution and diffusion of rock by igneous magmas have been substantiated by chemical evidence of a change in the intrusive magma due to such a reaction." Now, the writer believes that the more acidic patches or masses within the North Creek gabbro stocks do furnish strong evidence of chemical change within the intrusive igneous magma due to solution or partial solution and diffusion of blocks of country rock. In such cases the magma was just hot enough to melt or partially melt and only partially diffuse the blocks of country rock. Acidic masses formed in this way would not be expected to show

[1] *Natural History of Igneous Rocks*, p. 86.

[2] *Igneous Rocks*, I (1909), 281.

the diabasic texture. Obviously, examples of this kind would not be common.

The acidic (syenitic) border phase of stock No. 1 (see map) and represented by No. 10 of Table I might be explained on the basis of simple marginal assimilation, though there appears to be no good reason against explaining it as due to the assimilation of blocks of country rock stoped from the walls of the stock chamber. In accordance with Daly's hypothesis the blocks of country rock would have been derived from a level some distance above the present observed contact but, because of the low specific gravity of the country rock (granite) as compared with the molten gabbro, and also because of the superheated condition of this gabbro magma (as proved by the vigorous contact action on the granite), those blocks of country rock would not have sunk very far in the magma before they became thoroughly assimilated.

SIGNIFICANCE OF THE MORE ACIDIC STOCKS

Five or six of the stocks are composed of rocks more acidic than gabbro. Fine examples are: Stock No. 3 (see map); $1\frac{1}{3}$ miles northeast of Pottersville; $\frac{3}{4}$ of a mile south-southeast of South Horicon; and $1\frac{1}{4}$ miles southwest of The Glen. In fact every gradation may be found from stocks of basic gabbro, through acid gabbro and diorite, to syenite. In the earlier stage of very active intrusion the invading magma was more thoroughly molten, and as the blocks of country rock were stoped off they sank in the magma and became completely dissolved and diffused. Since the country rock was almost always granite, syenite, or gneiss, the magma became more and more acidic. A magma thus formed has been styled a "syntectic" magma. The amount of superheat required to dissolve the blocks would not be great because, as Daly has pointed out, there is plenty of proof that molten basic rock "even slightly superheated will dissolve fragments of gneiss and allied rocks. The mutual solution of two contrasted silicate mixtures takes place at a certain temperature which is lower than the melting-point of either one."[1] According to the specific

[1] *Amer. Jour. Sci.*, XXVI (1908), 36.

gravity figures given by Daly[1] on good authority it seems quite certain that most, at least, of the xenoliths would have sunk in the North Creek stock magmas during their highly molten early stages of intrusion.

The very close chemical relationship between the diabase and the typical gabbro pretty clearly shows the derivation of these rocks from a source of supply of such a basic composition, and that the acidic facies of the gabbro were somehow developed during the process of intrusion, more than likely by the assimilation of country rock. Where the normal basic rock now constitutes a stock is readily explained because in the later, less highly molten stage of intrusion, stoping would be greatly lessened and xenoliths would sink little if any, while this upward current of later basic magma would push the earlier formed, more acidic "syntectic" to a higher level in the vent. Where basic gabbro now fills a stock chamber simply means that the upper, more acidic assimilation product (syntectic) has been removed by erosion.

The objection may be raised that these stocks are too small to have had sufficient heat for the melting and diffusion of the xenoliths. But it must be remembered that the gabbro and its derivatives are true plutonic rocks, and that the portions of the stocks now at the surface were, at the time of intrusion, far below the surface. The fact that, in some cases, tongues of the intrusives have penetrated the country rock clearly argues for a highly fluid magma. Again, the very character of the distribution of the gabbros along distinct belts strongly suggests that the stock masses are merely offshoots from a much larger underground gabbro mass which, at the time of the intrusion, must have been more highly molten than the present surface exposures seem to indicate.

Thus the North Creek basic stocks appear to furnish fine illustrations of intrusions accompanied by more or less magmatic stoping and assimilation, so that we have all gradations from basic gabbro to syenite stocks, and from stocks in which magmatic assimilation produced true syntectic magmas, to those in which xenoliths were only partially dissolved and diffused, to those in which xenoliths were wholly undissolved.

[1] *Amer. Jour. Sci.*, XXVI (1908), 27–28.

LACK OF VARIATION OF THE DIABASE

Because of its remarkable homogeneity in composition, the diabase presents a marked contrast to the neighboring gabbro. The diabase never contains inclusions and never shows any evidence of magmatic assimilation even in the largest masses. This difference is quite certainly due to the difference in the mode and condition of intrusion, the diabase having clearly been forced through comparatively narrow fissures in the country rock and pretty near the earth's surface as the texture shows. In such intrusions magmatic stoping would be reduced to a minimum or absent.

"THE ORDER OF CRYSTALLIZATION IN IGNEOUS ROCKS"

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In a recent number of this *Journal* appeared an article entitled "The Order of Crystallization in Igneous Rocks."[1] A series of conclusions far-reaching in their effect on petrography are arrived at by the author, which are certainly worthy of further comment and discussion. By building up on certain fundamental assumptions, the author is enabled to give a series of diagrams showing for each of the important rock groups both the order of beginning and the order of cessation of crystallization. A further discussion of the assumptions seems, on account of the importance of the conclusions arrived at, very desirable.

In considering such a subject as the crystallization of a magma, we must first of all remember that we have to deal with a definite chemical system whose behavior is rigidly governed by the laws of mass action and the phase rule. The laws of physical chemistry should throw some light on this problem, and it is the purpose of the author to advance some ideas which may affect the conclusions arrived at in the above article.

Can we regard a granite and a rhyolite as representing the same chemical system? That is, may we in the full sense of the term regard a rhyolite as the quenched portion of the chemical system, which, if undisturbed, would result in a granite?

Geologists generally agree that the same magma, depending on certain variable conditions, such as temperature, pressure, and rate of cooling, may yield either a granite or a rhyolite, but probably none will maintain that these variable factors, and especially temperature and pressure, will have an effect only on the physical condition, but not also on the chemical condition of the magma. A granite consists not only of a solution of the various oxides in

[1] N. L. Bowen, *Journal of Geology*, XX, 455.

each other which subsequently enter into the formation of the different minerals in the rock, but there also enter in a series of volatile components such as water, boron, fluorine, chlorine, etc.—the mineralizers. How are these held in the magma? In all probability they are in certain molecular combination with some of the other oxides present. Under the conditions of great pressure and in the presence of mineralizers, a granite begins and completes crystallization. The effect of these volatile components is considered so important that the solidification temperatures of certain granites is placed as low as 200°–350° C.[1] These mineralizers are the powerful solvents, they represent to a large extent the "mother liquor" from which the granite crystallized.

Turn now to the case of a rhyolite. The variable factors are quite different. Pressure is far less, the rate of cooling is far more rapid. What will be the effect of such a change? In physical chemistry we recognize what is known as van't Hoff's law, which deals with the fact that displacements of equilibrium within a solution are effected by changes in temperature and pressure. Crystallization in a magma can be brought about in one case at a higher and in another case at a lower temperature, depending on the pressure. An increase of pressure will induce crystallization at a higher temperature. By a change of pressure equilibrium will be destroyed within the magma, and reactions taking place will go farther in one direction, thus altering the relative proportions of the various compounds present. As a result we may obtain in the rock an association of minerals quite different from what it would have been under a different pressure.[2] As a further result of decrease of pressure, the volatile constituents would escape, causing additional disturbance in the equilibrium and rearrangement in the molecular grouping, which will further influence the final crystallization product. Thus the law of mass action and van't Hoff's law seem to prove that granite and rhyolite cannot safely be regarded as having the same order of crystallization nor the same mineral make-up. The conception of mineralizers strengthens this view.

[1] Harker, *The Natural History of Igneous Rocks*, p. 189.

[2] Cf. C. N. Fenner, *American Journal of Science*, XXIX (March, 1910), 217.

If a solution crystallizes, is a recurrence of the first component to solidify possible, after complete crystallization of the other dissolved substances? We must concede as true that a magma represents a solution at high temperature, and that its crystallization must be analogous to the crystallization of any solution. Chemical precipitation due to chemical reaction caused by concentration, or by the elimination of some dissolved substance, may take place, but on the whole the analogy to a freezing salt solution should be striking. This has been pointed out repeatedly by various authors.

For comparison, let us recall Usiglio's classical experiments on the evaporation of sea-water. In this case we have a complex solution of such compounds as Fe_2O_3, $CaCO_3$, $CaSO_4$, NaCl, KCl, $MgSO_4$, $MgCl_2$, etc. Pressure and temperature were kept constant, but the degree of concentration was varied. The following order of crystallization was obtained: Fe_2O_3, $CaCO_3$, $CaSO_4 + 2\ H_2O$, NaCl, $MgSO_4$, $MgCl_2$, NaBr, KCl. There was an overlapping of the periods of crystallization, but in no case was there a recurrence of the crystallization of any member after a later product had formed (see fig. 1). When a salt solution freezes, ice crystallizes out, and the solution becomes more and more concentrated until saturation is reached (23.6 per cent NaCl); when at a temperature of $-22°$ C. both crystallize together, forming a cryohydrate. Salt does not crystallize out to be followed later by ice. Other examples of crystallization of salt solutions might be cited, but the above are sufficiently familiar and characteristic. In all cases (see Figs. 2, 3), however, no overlap of the first crystals formed can occur with regard to later products, as far as order of cessation of crystallization is concerned. In the majority of cases the end product should be a cryohydrate (eutectic).

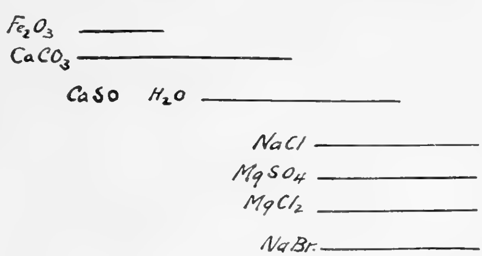

FIG. 1.—Order of crystallization upon partial evaporation of sea-water.

For a different case let us assume we have three metals fused into an alloy. Provided they are completely soluble in each other, the eutectic ratio is the controlling factor, the metal in greatest excess crystallizing first, until the second metal reaches its saturation point, when the two come down together, until finally the ternary eutectic point is reached and crystallization of all goes on simultaneously. In case the metals interact, chemical compounds may be formed and complicate the system. Thus in a combination

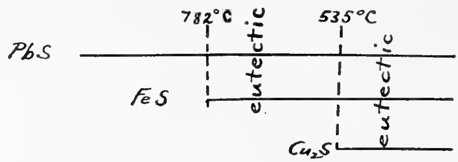

FIG. 2.—Order of crystallization in alloy of PbS = 70 per cent, FeS = 20 per cent, Cu_2S = 10 per cent.

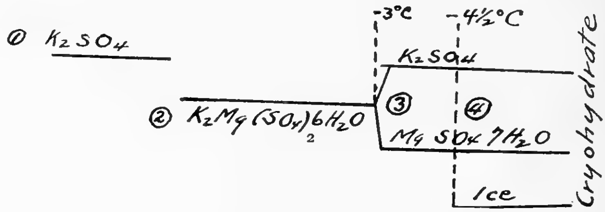

FIG. 3.—Crystallization of K and Mg sulphate solution, when K_2SO_4 is in excess and saturates solution between 92° and −3° C. Schönite ② is stable only between 92° and −3°C. See van't Hoff's *Theoretical and Physical Chemistry*, p. 86.

of bismuth, lead, and tin, the order of beginning of crystallization will depend on relative masses and will end with a ternary eutectic. In the case of a copper, tin, and antimony mixture, we get chemical reactions during cooling which may result in the formation of three pure metals and seven chemical compounds. There is no recurrence of the substance first crystallized in either case. If substances are capable of forming solid solutions they do not affect the above in any way.

For sake of simplicity let us assume we have a magma of SiO_2, $KAlSi_3O_8$, and $NaAlSi_3O_8$, an example worked out by Harker.[1]

[1] Harker, *Natural History of Igenous Rocks*, p. 251.

The order of crystallization will depend on relative masses, but will in every case end with a ternary eutectic. We all concede that the rate of growth of different crystals varies, but it does not seem probable that in the same solution one substance, such as quartz, begins solidifying before a second, say orthoclase, and also is still crystallizing after the latter is completely removed. Such overlapping would seem to be an unusual exception to the general rule, of which no example has been found. Considering this point, may we not assume that order of cessation of crystallization gives a definite clue to the order of beginning of crystallization?

SUMMARY

With a view of testing the conclusions as to order of crystallization, the author advances the following points:

1. We cannot assume that the effects of pressure and of crystallization temperatures may be considered negligible in the case of rhyolite and granite (effusive and deep-seated rocks). Therefore it is doubtful that we can assume the same order of crystallization or the same end-products.

2. We must recognize the importance of the mineralizers, not only as affecting the physical condition of the magma, but also its molecular arrangement, and consequently its manner and possibly, order of crystallization.

3. Comparing the order of crystallization in solutions and alloys, we find that the order of cessation of crystallization gives a definite clue as to the order of beginning of crystallization, consequently overlapping both of the beginning and the cessation of crystallization of any substance by another seems improbable.

The author is indebted to Professor M. F. Coolbaugh for valuable suggestions.

ANGISTORHINUS, A NEW GENUS OF PHYTOSAURIA FROM THE TRIAS OF WYOMING

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During the summer of 1904 a paleontological expedition from the University of Chicago, under the direction of Dr. S. W. Williston, made some valuable collections of vertebrate fossils from the Trias of Wyoming along the Popo Agie River. From these collections Dr. Williston described *Paleorhinus bransoni* and mentioned three other phytosaurian skulls,[1] all of which were collected by Drs. E. B. Branson and R. L. Moodie. Dr. Williston has very kindly granted the writer the permission to study these phytosaurs and it is from this material that the following notes are drawn. Considerable time and patience have been required of Mr. Paul C. Miller in the preparation of two of these skulls for mounting and the work is not yet completed. In all probability it will be some time before a full description with figures of these specimens is possible and for this reason it seems advisable to give a brief diagnosis of a new form represented by them for the benefit of others that may be studying this group of reptiles.

Angistorhinus grandis, Gen. and Sp. Nov.

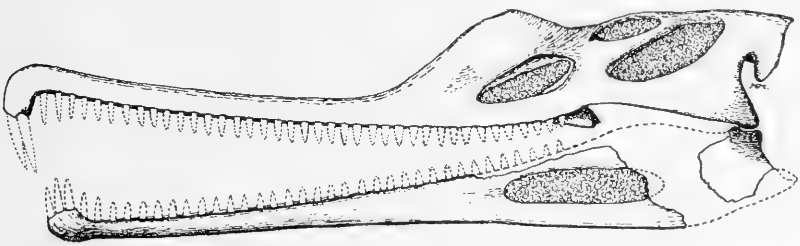
This form is represented by a nearly complete skull and a mandible of which the right ramus, back of the symphysis, is missing, as is a small part of the left ramus. Many limb bones, dorsal plates, and other fragments were found in the same locality with the skull and may belong to this species.

In a lateral view the skull resembles very closely that of *Mystriosuchus* Fraas.[2] The premaxilla, as in *Mystriosuchus*, are

[1] "Notice of Some New Reptiles from the Upper Trias of Wyoming," *Jour. Geol.*, XII (1904), 696.

[2] *Die Schwabischer Trias-Saurier nach dem Material der Kgl. Naturalien-Sammlung in Stuttgart zusammengestellt* (1896), p. 16, Pl. V.

produced into a long, slender, subcylindrical rostrum. Near the anterior end the rostrum expands rather rapidly and is bent abruptly downward at right angles to the axis of the posterior portion. This downward extension reaches a distance of 35 mm. below the ventral plane of the rostrum. The anterior border of the nares is about even with the anterior border of the antorbital vacuity and about 590 mm. from the tip of the rostrum. The nares are elevated on a prominence that extends slightly above the plane of the inter-orbital region. This prominence is accentuated by a saddle-shaped depression immediately back of the nares. The antorbital vacuities are large and are oval in outline, about 130 mm. long and 55 mm. wide. The orbits are separated by an inter-orbital space of 68 mm. They are oval, about 89 mm. long and 55 mm. wide, and their



Skull and mandible of *Angistorhinus grandis.* Lateral view, about one-ninth natural size.

planes are directed outward and a little less upward. The latero-temporal fenestrae are exceptionally large, being about 171 mm. along the greatest diameter. They reach back and upward to such an extent that only a narrow bar of bone separates the supra-temporal and the latero-temporal fenestrae. The supra-temporal fenestrae are large, more or less oval in outline, about 84 mm. long and 46 mm. wide. The posterior border, the parieto-squamosal arcade, is well developed. It is formed by a rather broad, platelike bone (the sutures have not yet been made out) that lies in the plane that extends over the posterior dorsal surface of the skull. The posterior border of the skull, as seen from above, is incised by a broad, rather deep notch. Still, the posterior border of the parietals at the median line extends beyond the occipital condyle fully 11 mm. The downward extension of the postero-lateral portion of the

squamosal of *Mystriosuchus planirostris* has an even greater development in this form. The hooklike process in *A. grandis* extends below the plane of the dorsal surface of the skull a distance of about 104 mm. Although all the teeth but the roots of the anterior ones have dropped from the alveoli, a fairly good idea of the dentition can be gained. The downward extension of the rostrum contains four teeth, sections of the roots of which show a diameter of about 15 mm. The anterior teeth of another specimen (described below), although of less diameter, reach a length of about 78 mm., a fact that would bespeak a still greater length for the anterior teeth of *A. grandis*. Sections through the rostrum disclosed teeth that had not yet been erupted. These, as many others found loose in the matrix, were laterally compressed with anterior and posterior sharp, finely serrate, cutting edges.

The differences between *Angistorhinus* and the forms that it resembles seem evident. From *Mystriosuchus* it differs in possession of laterally compressed posterior teeth with sharp, more or less serrate cutting edges. Quoting Dr. E. Fraas (*op. cit.*, p. 16): "Die Zähne selbst sind auch nicht glatt und mit scharfer Kante versehen, sondern schwach gerieft und von rundem Querschnitt ohne Kante, sie gleichen am meisten den *Nothosaurus*-Zähnen aus den Bonebeds. Dass eine Species mit derartigen Zähnen nicht gut *Belodon* (Pfeilzahn) genannt werden kan, wird man mir zugaben."

McGregor has characterized not only *Mystriosuchus*, but the entire suborder, Phytosauria, as having the parieto-squamosal arcade greatly reduced and depressed.[1] In *Angistorhinus* this is decidedly not the case; the arcade is well developed and lies in the plane of the posterior dorsal surface of the skull.

From *Rhytidodon carolinensis* Emmons[2] *Angistorhinus* differs considerably in the development and position of the parieto-squamosal arcade, for *Rhytidodon* and *Mystriosuchus* seem to be very similar in this respect. To quote Dr. McGregor (*op. cit.*, p.

[1] *Memoirs of the Amer. Mus. of Nat. Hist.*, IX, Part II (1896), 92.

[2] This is the genus and species recognized by McGregor (*ibid.*, p. 95). F. von Huene (*Beiträge zur Kenntnis und Beurteilung der Parasuchier*, 1911, p. 42) has included *Rhytidodon* in the genus *Mystriosuchus*, but Emmons' genus seems to stand, as the teeth are shown by McGregor to be laterally compressed, some with cutting edges, whereas, as pointed out above, the teeth in *Mystriosuchus* are all round in cross-section.

58): "In this specimen [a specimen of *R. carolinensis* from the U.S. Nat. Mus.] the broad superficial portion of the post-fronto squamosal arcades is broken away, exposing the supratemporal fenestra and the parieto-squamosal arcade. If uninjured this portion of the skull would closely resemble that of *Mystriosuchus*. . . . ."

There is no good basis for the comparison of *Angistorhinus* with *Phytosaurus* (*Heterodontosuchus*) *ganei* Lucas,[1] as until recently only the anterior part of an imperfect mandible of the latter form was known. In this, according to Lucas, the teeth were separated by a thin film of bone only, while in *Angistorhinus* they are separated by a distance of from 4 mm. to 8 mm. Furthermore, the examination of more recently obtained material suggests, at least, that *Heterodontosuchus* belongs to the genus *Phytosaurus* (McGregor, *op. cit.*, p. 94). In this case the differences in the posterior border of the skulls would exist as pointed out above.

Angistorhinus differs from *Paleorhinus bransoni* Williston[2] in many minor points such as the greater posterior width of the skull in the former, the greater lateral extent of the opisthotics, the larger openings in the skull, the abrupt downturning of the anterior end of the rostrum, and the much more massive build of the skull throughout. Most important of the differences, however, is the more primitive, that is, the more anterior position of the external nares in *Paleorhinus*. In that form the posterior border of the nares lies fully 30 mm. in front of the anterior borders of the antorbital vacuities, while in *Angistorhinus* the anterior border of the nares is about even with the anterior borders of the antorbital vacuities.

While *Angistorhinus* resembles *Mesorhinus Fraasi* Jaekel[3] in the form and development of the parieto-squamosal arcade, the two forms differ markedly in that the latter possesses a parietal foramen, according to Jaekel, and has the external nares more anterior in position. The downward process from the upper posterior side of the squamosal seems to be lacking in *Mesorhinus*, and the basi-

[1] *Amer. Jour. Sci.* (4), VI (1898), 399.

[2] J. H. Lees, *Jour. Geol.* XV, No. 2 (1907).

[3] "Uber einen neuen Belodonten aus dem Buntsandstein von Bernburg," *Sitzungsberichten der Gesellschaft Naturforschender Freunde*, No. 5, Jahrgang 1910.

cranial region seems to extend back much farther than in *Angistorhinus;* to such an extent, in fact, that the basioccipital is plainly visible in a dorsal view in the former. The following table of measurements of *Angistorhinus grandis* may be found useful in comparing it with other forms.

Greatest length of skull	977 mm.
Length of skull from quadrates to tip of rostrum	909
Length from nares to tip of rostrum	590
Length from anterior borders of orbits to tip	755
Inter-orbital width	68
Greatest width of skull about	390

Another specimen of *Angistorhinus* is represented by a skull, the mandible, and apparently a nearly complete skeleton. The posterior end of the mandible and the upper posterior part of the skull are missing, but these may be contained in the unpacked slabs. In general appearance this specimen is the counterpart of *A. grandis* though smaller and more slenderly built. It can hardly be considered a young individual of *A. grandis*, however, as some of the following differences in the rostrum will show. In the second specimen the slender rostrum starts much more abruptly in front of the antorbital vacuity than in *A. grandis.* While the smaller skull is considerably compressed laterally, and lateral measurements are, therefore, of less value than longitudinal ones, the rostrum seems but little affected by this compression and the following measurements seem to show the differences well. At a point 140 mm. in front of the antorbital vacuity the width of the rostrum is about 56 mm. (some allowance is here made for compression), while at the same distance in front of the antorbital vacuity in *A. grandis* the width is about 94 mm. This is exactly the opposite of what one would expect if the former specimen were but the young and the latter the adult of the same species. In *A. grandis* the terminal expansion is just back of the downward extension and the expanded portion includes but four teeth. In the smaller specimen, however, the expansion takes place suddenly just back of the second tooth behind the downward extension and from this point to the extremity the lateral outlines of the rostrum are approximately parallel. Eight teeth are included in the anterior expanded part

of this rostrum, four on each side. On the right side three of these are preserved. The first, the posterior one of these, reaches a length of 69 mm. The second is missing. In the downward extension the lateral tooth is 78 mm. long and the inner one, probably a young tooth, is about 35 mm. long.

The anterior end of the mandible is expanded in a horizontal plane, while in that of *A. grandis* the sides of the anterior expansion are turned up, thus forming a deep, rounded groove along the median line. The terminal expansion in each form bears three large teeth with approximately circular section. Immediately back of these large terminal teeth the diameter of the teeth in *A. grandis* is from 7 mm. to 9 mm., while in the second specimen the diameter is from 5 mm. to 7 mm. In much probability further study will show that the skulls belong to two different species.

Reviews

Earth Features and Their Meaning. An Introduction to Geology. By William H. Hobbs. New York: Macmillan, 1912. Pp. xl, 506 illustrations, maps, appendices, index.

While the subtitle would class the book with texts in geology the first title is much more appropriate, and suggests the author's unique point of view. The work should be classed with Geikie's *Earth Sculpture* and Marr's *Scientific Study of Scenery*, but it is much more ambitious. The author has here expanded the substance of his own course of lectures on the subject in the University of Michigan.

As a textbook in geology it endeavors to cover only dynamic and structural geology. In the thirty-one chapters these two fields are well covered. The figure of the earth and its materials are described, and then discussed as to origin, nature, and interpretation. Rock structures, after careful description, are analyzed to get at their history, and to discover their effect on topography. The "character lines" of forms due to weathering, streams, ground water, waves, glaciers, sun and wind without much rain, and diastrophism are described, genetically correlated, and illustrated by line drawings, block diagrams, and sketches from photographs. Rarely are photographs reproduced without adapting by cutting out the non-essential and presenting in lines and symbols the essential. Twenty-four plates—photographs—against about 500 figures are used.

With a conscious effort to illustrate the theoretic work from American features the author has, possibly unconsciously, given a rather large place to glaciers, 140 pages out of about 500. No other overweighting seems apparent.

The introduction of much experimental data, and the forcing of the reader to go out and see things mentioned constitute a very valuable feature. Extended lists of reading references at the end of each chapter put the reader in touch with much of the best literature on the various topics. Appendices for the determination of minerals and rocks, and for the preparation, interpretation, and care of topographic and geologic maps are followed by a list of suggested itineraries for geologic study both in America and in Europe.

The student of physiography will find much more than the geologist in the work. The boundary line between the two sciences is pretty well concealed. Physiography is made to contribute to geologic interpretation and a wealth of data are furnished, ready to be applied to the elucidation of stratigraphic problems. G. D. H.

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CHEMICAL COMPOSITION AS A CRITERION IN IDENTIFYING METAMORPHOSED SEDIMENTS[1]

EDSON S. BASTIN
U.S. Geological Survey, Washington, D.C.

I

In 1909 the writer contributed to this *Journal*[2] an article under the title given above. In the present pages it is his desire to correct some apparent misunderstandings of the import of the data there presented and to offer some additional data since obtained.

The idea that chemical composition may in some cases furnish a clue to the origin of a metamorphic rock is nothing new. It was formulated in general terms by Rosenbusch and has been given recognition by Grubenmann, Van Hise, Adams, and others.

The postulate is a very simple one, namely: that certain well-known and characteristic changes in chemical composition produced in the processes of rock weathering and assortment may be recognizable even when the resulting product has been dynamically metamorphosed.

The writer in his previous article attempted to test with some care the value of each of the chemical criteria which earlier writers had suggested, and the method adopted was the comparison of

[1] Published with the permission of the Director of the U.S. Geological Survey.

[2] *Jour. Geol.*, XVII (1909), 445–72.

analyses of a large number of sedimentary slates and schists with a much larger number of analyses of igneous rocks. Such a statistical study, the assembling of analyses which were selected judiciously but impartially, offered, he believed, a viewpoint from which the *rule* could be perceived in the midst of the numerous *exceptions* which special conditions introduce. The result of this study was to confirm in general the beliefs of the geologists who had earlier considered this problem. In addition conclusions were reached as to the relative critical value of various chemical relationships.

J. D. Trueman in a recent number of this *Journal*[1] summarized in a very useful manner the various criteria that had been applied for determining the origin of schists. In the section devoted to chemical criteria he recognized that these may be of service in some instances, but he seemed in general inclined to attribute small importance to them.

As Mr. Trueman was good enough to refer to my article on this subject, I wish here to consider some of the objections which he raised and to elucidate further certain of the arguments that were brought forward in the original paper. Mr. Trueman's untimely death last summer while engaged in geologic field work must be a source of deep regret to those who are familiar with his work and I take this opportunity to express my appreciation of the high value of the contribution he has made to the literature on metamorphism. Agreeing with most of his conclusions, if I take exception to a few of them it is in the belief that no true scientist regards his results as final but is eminently satisfied if his work stimulates others and contributes somewhat to the progress toward a more complete knowledge of Nature's laws.

The principal criteria which have been appealed to in support of sedimentary origin of a fresh crystalline schist are: (1) dominance of magnesia over lime, (2) dominance of potash over soda, (3) the presence of alumina in large excess over the 1:1 ratio necessary to satisfy the alkalies present. It should be particularly emphasized that the *amount of the excess* of potash, magnesia, or alumina is of great importance, a magnesia-lime ratio of 4:1 being immensely

[1] *Jour. Geol.*, XX, No. 4, pp. 300–311.

more significant than a $1\frac{1}{2}:1$ ratio, and 10 per cent excess alumina having several times the diagnostic value of a 5 per cent excess.

In attempting to compare in a general way the *relative* merits of various chemical criteria, the writer possibly conveyed a stronger impression of their individual worth and potency than he would at present desire to do. Few reputable physicians are content to diagnose a disease from a single symptom, but when several symptoms all point to a common cause a diagnosis may be made with security. To follow the parallel, the chemical relationships used as criteria are symptoms which considered singly might result from several causes, but taken collectively are known to result from only one[1] cause, rock weathering and assortment. In actual practice the geologist is seldom required to depend entirely upon chemical criteria but is aided in his diagnosis by structural and textural features as well.

The principal results of the writer's comparisons of analyses of meta-sedimentary with igneous rocks may be summed up in the following table in which the figures in parentheses show the number of analyses of each class of rocks entering into the comparison.

TABLE I

		Percentage Weight of $MgO > CaO$	Percentage Weight of $K_2O > Na_2O$	Percentage Weights of Both $MgO > CaO$ and $K_2O > Na_2O$	Over 5 Per Cent Excess* Al_2O_3	Over 10 Per Cent Excess* Al_2O_3
Sedimentary slates......		(79) 84 per cent	(74) 92 per cent	(74) 78 per cent	......	......
Pelite schists and gneisses..............		(30) 77 per cent	(30) 83 per cent	(30) 74 per cent	(30) 63 per cent	(30) 30 per cent
Igneous rocks of Washington's *Tables of Analyses*	Classes I and II..	(1481) 8 per cent	(1481) $36\frac{1}{2}$ per cent	(1481) $4\frac{1}{2}$ per cent	(1892) Less than 3 per cent	(1892) About 0.6 per cent
	All other classes...	(411) 35 per cent	(401) 14 per cent	(401) 7 per cent		

*By "Excess Al_2O_3" is meant the alumina in excess over the 1:1 ratio in which it is combined with lime and the alkalies in the aluminous silicates. If the "norm" is calculated according to the method of the *Quantitative Classification of Igneous Rocks*, this excess appears as corundum.

The meaning of the table may be made clearer by interpreting its third column. This column shows that of 74 analyses of sedi-

[1] A partial exception in hydrothermal metamorphism will be referred to later.

mentary slates 78 per cent showed a dominance both of magnesia over lime and of potash over soda. In 70 analyses of pelitic schists and gneisses this relationship is almost equally characteristic, holding in 74 per cent of the analyses. In the more siliceous igneous rocks (Classes I and II), on the other hand, dominance of magnesia over lime and of potash over soda occurs in only 4½ per cent of the 1,481 analyses considered, and in the case of all the other igneous rocks (Classes III, IV, and V) in only 7 per cent of the 401 analyses considered. The contrast between igneous rocks and sediments shown in the other columns is also striking. Such wide differences as are here exhibited can hardly be fortuitous, and the nature of data upon which they are based would seem to recommend them to the serious consideration of geologists.

In criticism of the value of the potash-soda and magnesia-lime ratios as criteria of genesis, Mr. Trueman[1] states that "in the case of many, possibly in the majority of, igneous rocks *either* the MgO is in excess over the CaO or the K_2O over the Na_2O . . . ." and points out with perfect correctness that "the tables of Washington show that in the majority of igneous rocks *containing over 70 per cent of silica* the K_2O is in excess over Na_2O. . . . . Accordingly while the double relationship is apparently significant, the single ratios have but little value."

To the present writer there would seem to be no valid reason for restricting the comparison to those igneous rocks which show more than 70 per cent of silica, especially as these include nearly all of the greatest group of potash-rich rocks, the granites and rhyolites, and also as the average percentage of silica in the metasedimentary rocks with which they are compared is only 60 to 65 per cent. While the double relationship $\left\{\begin{matrix} K_2O > Na_2O \\ \text{and} \\ MgO > CaO \end{matrix}\right\}$ is the most significant and the single relationship of $K_2O > Na_2O$ or $MgO > CaO$ is of little or no critical importance when standing alone, the writer believes that either of these relations, if supported by notable excess of alumina, has very considerable critical value.

Each of the criteria suggested has its "limit of error" which

[1] *Op. cit.*, p. 301.

with the data at present available cannot be determined. For this reason the criteria cannot be applied automatically without the exercise of judgment and discretion on the part of the investigator. It should be especially remembered that if the rocks under investigation have been subjected, either before or after the development of their foliated structure, to severe igneous or hydrothermal

TABLE II

	I	II	III
SiO_2	57.35	49.59	61.62
Al_2O_3	16.29	14.91	19.98
Fe_2O_3	3.15	.52	3.46
FeO	4.36	10.46	2.57
MgO	2.41	2.02	1.24
CaO	5.66	1.96	.62
Na_2O	4.50	1.33	1.78
K_2O	3.39	3.51	5.35
H_2O-	.15	.16	.21
H_2O+	.70	3.17	2.23
TiO_2	1.07	1.03	.56
ZrO_2	tr.	none	
CO_2	.46	9.40	
P_2O_5	.70	.47	
MnO	.12	1.10	
Others	.24	.43	
Total	100.55	100.06	99.62

I. Fresh diorite porphyry 25 feet from vein, Wellington mine, Breckenridge, Colo. W. T. Schaller, analyst.

II. Altered diorite porphyry 10 feet from vein, Wellington mine, Breckenridge, Colo. W. T. Schaller, analyst.

III. Pinal schist, Ray district, Arizona. Analysis made for Dr. F. L. Ransome by R. C. Wells.

metamorphism, the criteria are not applicable, for such metamorphism involves important additions and losses of material. For example, analyses I and II of Table II taken from Dr. Ransome's report on the Breckenridge district, Colorado,[1] show that in the hydrothermal metamorphism of a diorite porphyry there has been a much greater depletion in lime than in magnesia and that there has been an accession of potash and loss of soda, yielding a rock in which the double relationship $\left\{\begin{matrix} K_2O > Na_2O \\ \text{and} \\ MgO > CaO \end{matrix}\right\}$ is present.

[1] F. L. Ransome, "Geology and Ore Deposits of the Breckenridge District, Colorado," *Prof. Paper U.S. Geol. Surv. No. 75* (1911), p. 96.

The same result is brought about by the hydrothermal alteration of monzonite porphyry in the Clifton-Morenci district as described by Lindgren,[1] and Dr. A. C. Spencer has shown the writer unpublished analyses exhibiting similar changes as a result of hydrothermal metamorphism of porphyry in the Ely district, Nevada. It is evident therefore that the chemical criteria must be applied only to those foliated rocks which the microscope shows have *not* been subsequently subjected to weathering or to igneous or hydrothermal metamorphism, in other words, to *fresh* foliated rocks. In those rare instances where igneous or hydrothermal metamorphism has affected the rocks previous to the development of foliation there should usually be some evidence of it in the presence of mineralization in associated schists.

An instance of the successful application of chemical criteria as an aid to determining the origin of a schist in a mining district is afforded by analysis III of Table II, hitherto unpublished, which I have been permitted to use through the courtesy of Dr. F. L. Ransome. This schist consists predominantly of quartz and sericite with subordinate chlorite, biotite, andalusite, magnetite, and zircon. It forms part of the Pinal schist of the Ray district, Arizona, which is shown by bands of pebbles, arkosic and quartzitic phases to be for the most part of sedimentary origin. This schist is older than the mineralization, and microscopic study indicates that the specimen analyzed has suffered no important mineral changes since the development of the foliation. It will be noted that there is about twice as much magnesia as lime in this rock and about three times as much potash as soda. Alumina is present to the extent of 10.30 per cent above that necessary to satisfy the lime and alkalies present. The strong development in this rock of these three chemical characteristics points to its having been subjected to the processes of weathering and assortment previous to metamorphism, in other words, indicates a sedimentary origin, and affords, the writer believes, a valuable *adjunct* to textural and structural evidences in interpreting the origin of the rock.

[1] W. Lindgren, "The Copper Deposits of the Clifton-Morenci District, Arizona," *Prof. Paper U.S. Geol. Surv., No. 43* (1905), p. 168.

II

The question of the value of chemical criteria is part of the much broader question of the extent to which transfer of material goes on in rocks during purely dynamic metamorphism. This is a problem of importance to geologists and one which has received little attention. The data at present available are of somewhat conflicting character. Certainly many who have worked in regions of metamorphic schists must have been impressed by the extent to which portions of the metamorphic series, originally different, have preserved their individuality. Dikes, though rendered schistose and perhaps pinched out in places, still show sharp borders giving no evidence of extensive interchange of material with the bordering rock; limestone beds in the series still show sharp borders after metamorphism, and original sedimentary beds may still be recognized as such by the development of *knoten* or of particular minerals in some of them and not in others. In rarer cases ore deposits have been deformed in dynamic metamorphism without destroying the integrity of the ore bodies or causing any migration of the ores into the wall rocks as in the case of the Milan, N.H., deposit described by Emmons.[1]

As the writer pointed out in his earlier paper,[2] many of the granite-gneisses of Georgia described by Dr. Watson are still normal granites in composition although showing marked evidence of dynamo-metamorphism. To quote Dr. Watson:[3] ". . . . the granite-gneisses differ from the more massive rock phases [granite] simply in the marked banded or foliated structure. These are secondary structures induced by profound and long-continued dynamo-metamorphism, acting on an originally massive rock, similar, in mineralogical and chemical compositions, to the existing massive granite areas studied."

If it can be shown that important transfers of material may take place during dynamo-metamorphism, it still remains to be determined whether such processes are common or exceptional in the

[1] W. H. Emmons, "Some Ore Deposits in Maine and New Hampshire," *Bull. U.S. Geol. Surv., No. 432* (1910), pp. 50–60.

[2] *Jour. Geol.*, XVII (1909), 450–51.

[3] *Bull. 9-a, Geol. Surv. of Georgia*, p. 263.

metamorphic rocks now exposed at the earth's surface. It is commonly supposed that under conditions of dynamo-metamorphism rocks are relatively dry and pore-space is reduced to a minimum and such conditions would appear to be particularly unfavorable for the transportation of material through long distances in solution. Certainly the writer has seen little in his personal experience with the crystalline schists of New England and the Rocky Mountains to suggest migration of material under such conditions through more than very small distances. A number of years ago the writer, by averaging a very large number of analyses of clays, shales, slates, and pelite schists, attempted to prepare a series of curves to illustrate the chemical changes during the metamorphism of a clay into a pelite schist. The data used were not regarded as sufficiently complete in all particulars to justify publishing the curves. They showed marked loss of water and carbon dioxide but were suggestive of considerable stability in most of the other constituents, with the possible exception of silica.

It is well known that the development of platy minerals is a characteristic feature in dynamo-metamorphism. From the department of geology of the University of Wisconsin has come the suggestion that this process may exert a controlling influence upon the composition of the rock, constituents unnecessary for the formation of the platy minerals being removed during the progress of the dynamo-metamorphism. While suggested as a general law, the actual evidence thus far offered in support of this hypothesis has involved only the expulsion of silica from highly siliceous rocks. The data offered by Mr. Trueman[1] in evidence of such transportation of silica in the Waterloo quartzite of Wisconsin are suggestive and all similar data should become a matter of record. It is shown that while some bands of sericite schist parallel the bedding planes of the quartzite, others transgress them, and it is argued that the sericite schist of these transgressing shear zones has been produced directly from the impure quartzite by the expulsion of silica during the shearing process. Other hypotheses are, however, worthy of consideration. The zones of sericite schist which transgress the bedding planes may represent

[1] *Op. cit.*, pp. 302–6.

fracture zones which later became the locus of shearing movements. All that is required to produce the chemical changes observed is the removal of silica by waters circulating along such fractures. It is also impossible in this region to eliminate the possible effect of igneous rocks as a source of energy which might result in such changes. The Waterloo quartzite outcrops only in small ledges separated by large areas covered by glacial drift. Pegmatites which appear to be earlier than the shearing of the quartzite cut this rock in certain of the ledges. Although no pegmatite outcrops at the locality where the samples analyzed were taken, it is impossible to say that it does not occur close by beneath the drift cover.

Whatever may be the facts in regard to the mobility of silica under certain conditions, it is beyond question that in the metamorphism of many sedimentary series the quartzite members preserve their integrity even when the associated argillaceous beds are rendered highly schistose, nor do the latter show any marked accession of silica. It has been suggested that a talc schist is the characteristic metamorphic equivalent of limestone as a sericite schist is of quartzite, but here again we are confronted with numerous field observations showing abrupt passages from crystalline limestones to argillaceous schists and to quartzites, even in severely metamorphosed series. Furthermore, with the possible exception of the expulsion of silica, the development of platy minerals during dynamo-metamorphism would seem to be a process ill suited to the accomplishment of any considerable changes in chemical composition, for the platy minerals that are characteristically developed in schists during dynamo-metamorphism are minerals of extremely variable composition, and the same elements enter into the makeup of a number of them. For this reason they are especially adapted to *accommodate* original differences in composition both through variation in the relative proportions of the different platy minerals developed and through variations in composition of each of these minerals.

WASHINGTON, D.C.
December, 1912

OBSERVATIONS ON THE FELDSPARS

AUSTIN F. ROGERS
Leland Stanford Junior University

A PECULIAR PERTHITE FROM PORT HENRY, N.Y.[1]

An interesting variation of the albite-microcline intergrowth known as perthite was noticed among some specimens obtained from a mineral dealer. The body of the specimen is pale flesh-red microcline. On the basal pinacoidal {010} cleavage there are two intersecting sets of narrow, colorless albite strips, which are plates inserted parallel to the unit prism {110} (Fig. 1). The peculiarity is that the two sets of albite plates are twinned with respect to each other on the albite law. This can be demonstrated by holding

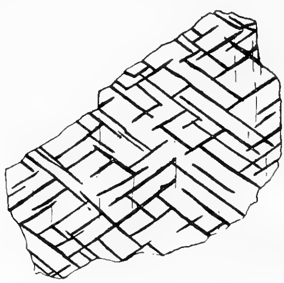


FIG. 1.—Peculiar perthite ($\frac{1}{2}$ natural size).

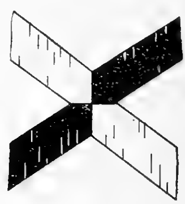


FIG. 2.—Albite from perthite (magnified).

a specimen with the basal cleavage close to the eye. A reflection being obtained from the microcline cleavage, on revolving the specimen about the *a*-axis a little toward one, there is a reflection from the albite plates parallel to the (110) face, and on revolving it a little in the opposite direction, there is a reflection from the albite plates parallel to the ($1\bar{1}0$) face. In each case the reflection is from the basal {001} cleavage. The angle between the (001)

[1] This perthite, as well as the albite described in the next item, are evidently from pegmatites. See Kemp. *Trans. Am. Inst. Min. Eng.*, XXVI, 195 (1897).

face of the microcline and the (001) face of albite on each side is $3\frac{1}{2}°$ as measured with the simple reflection goniometer.

A microscopic examination confirms the above. A section parallel to the base {001} shows the gridiron structure for the microcline and plates of albite with extinction angles of about $3\frac{1}{2}°$. The albite plates parallel to the (110) face have extinction in the opposite direction from those parallel to the $(1\bar{1}0)$ face. Close examination reveals a few narrow twin lamellae in each set of albite plates. Fig. 2 is a diagrammatic drawing of a thin section cut parallel to (001).

The question arises as to whether this intergrowth can be called perthite or not. In the original perthite the albite plates are polysynthetically twinned and are parallel or approximately parallel to the *a*-axis. There is before me a specimen from the original locality, Perth, Canada (Fig. 3), which shows a coalescence of albite plates practically forming a plate parallel to the (110) face. I have also noted albite plates parallel to (110) in microcline-perthite from Rincon, Cal. On account of the gradation between the typical perthite and the peculiar perthite, it seems advisable to extend the term perthite to cover such cases. It should also be mentioned that normal perthite occurs among the Port Henry specimens. These specimens consist of microcline with plates of albite set parallel to the {100} face. They show polysynthetic albite twinning.

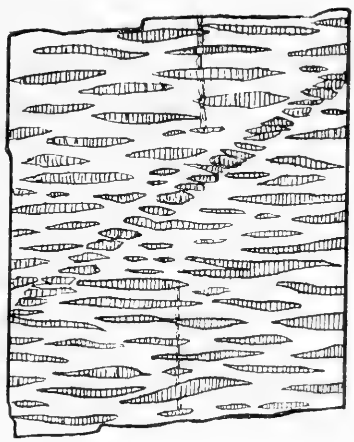


Fig. 3.—Perthite

ALBITE WITH BRACHYPINACOIDAL PARTING

Some cleavable albite of pale-green color from Port Henry, N.Y., consists of two kinds of specimens. Part of the specimens break in plates parallel to basal {010} cleavage while others break in plates parallel to the side pinacoid {010} and have a lamellar

structure. In albite the basal cleavage is perfect and the side pinacoidal cleavage, imperfect, hence the lamellar specimens are abnormal. A close examination of the two kinds of specimens shows polysynthetic twinning according to the albite law. In the basal cleavage of the first-mentioned variety the twinning lamellae are fairly uniform. Fig. 4 represents the basal cleavage of the variety with lamellar structure. Most of the twinning lamellae are very narrow, but every fifth to tenth one is much wider. On tracing the wider lamellae to the edge of the specimen there is usually noticed a parting plane. These parting planes are covered with a thin film of chlorite. In a specimen about 1 cm. wide there are about twenty-two broad lamellae and about twenty parting planes. The films of chlorite are probably the result, not the primary cause, of the parting, for the normal albite has finely divided chlorite all through it and not concentrated in films.

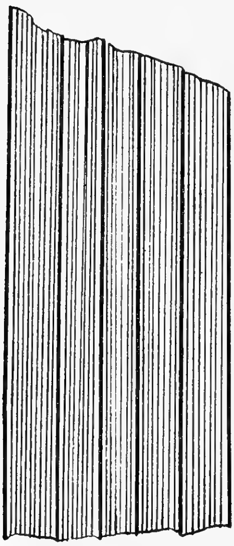


FIG. 4.—Albite twinning on albite (magnified).

If my observations are correct, there is both cleavage and parting in the same direction, namely, parallel to {010}. I know of no other similar case on record but there seems to be no reason why the same direction cannot be one of molecular disturbance as well as one of weak cohesion.

PERICLINE PARTING IN PLAGIOCLASE

Cleavable white plagioclase from Amelia Co., Va., shows a dull surface with bright spots. The bright spots are cleavage surfaces parallel to the base {001}. The dull surface is a plane of separation parallel to the rhombic section, for pericline twin lamellae are visible on the imperfect {010} cleavage. A glass slip was cemented on the dull surface and the angle between it and the cleavage measured with the reflecting goniometer. The angle is $+9°$, which places the plagioclase as albite-oligoclase, Ab_6An_1. Fig. 5 is a side elevation showing the cleavage, parting, and pericline twin lamellae.

I also have a specimen of albite from Auburn, Me., which shows pericline parting. The angle between the cleavage and the parting is $+13^{\circ}$, as nearly as can be measured with a contact goniometer, which places it as about $Ab_{12} An_1$. In this specimen there is pericline twinning as well as albite twinning and good cleavage parallel to $\{001\}$, $\{110\}$, $\{1\bar{1}0\}$, and $\{010\}$. The mineral splits easily parallel to $\{010\}$, and hence there is both parting and cleavage parallel to this face. The extinction angle on the (010) face is about 20°.

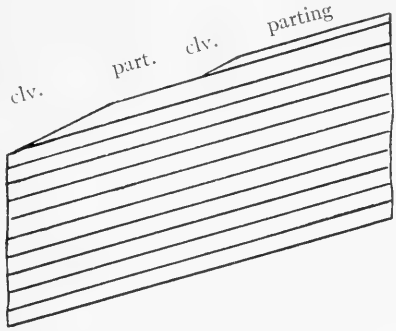


FIG. 5.—Albite-oligoclase, Ab_6An_1

Pericline parting was also noticed on a specimen of oligoclase from Bamle, Norway. A cover-glass was cemented to the dull parting surface and the angle between it and the cleavage was found to be $+3^{\circ}\ 50'$, measuring with the contact goniometer. This measurement places the feldspar as about Ab_3An_1, which is confirmed by the extinction angle of 0° on the (010) cleavage face.

For another plagioclase from Labrador, showing well-defined pericline twinning and only faint albite twinning, the cleavage and the parting are parallel, as nearly as can be judged. Even in this case there is lamellar structure due to pericline parting. According to Penfield and Sperry[1] the angle of the rhombic section for Ab_1An_1 is $\pm 0^{\circ}$. This places the feldspar as andesine-labradorite, which is confirmed by the extinction angle of -15° on (010).

PRISMATIC CLEAVAGE IN THE FELDSPARS

Labradorite from Labrador also occasionally shows dull surfaces due to pericline twinning. These dull surfaces are almost parallel to the cleavage, but careful measurement with the reflection goniometer proves the angle between the cleavage and the parting (using a cover-glass on the latter) to be about $-3^{\circ}\ 40'$

[1] *Am. Jour. Sci.*,(3) XXXIV, 390 (1887).

(average of 4° 5′ and 3° 15′). This proves the labradorite to be about $Ab_2\ An_3$. Fig. 6 is a side elevation of this labradorite.

The imperfect cleavage parallel to the unit form {110} or {110} and {1$\bar{1}$0} in the feldspars has not been sufficiently emphasized. It is present in nearly every specimen of the common feldspars which I have examined and is a valuable aid in orienting cleavages and imperfect crystals. Were it not for the prismatic cleavage, it would often be impossible to orient the feldspar and hence to determine the kind of feldspar. Even when not distinct, its intersection with (010) gives the direction of the *c*-axis.

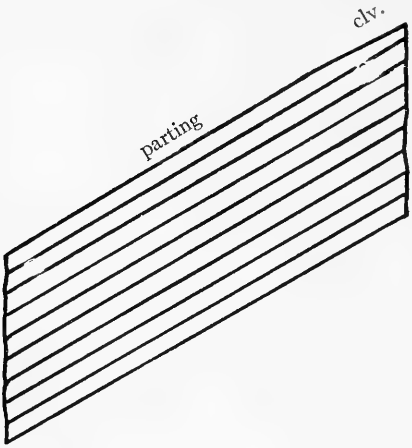


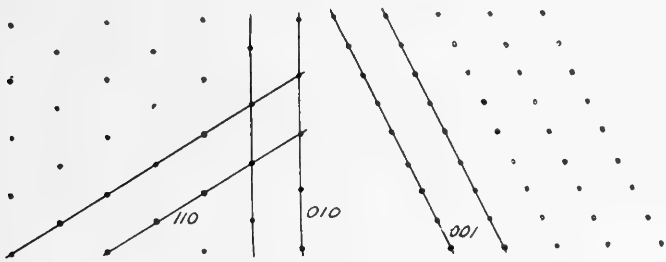
FIG. 6.—Labradorite, Ab_2An_3

That this plane of separation is cleavage and not parting is probable from a consideration of the internal structure of orthoclase. There are two possible space-lattices for monoclinic crystals, the monoclinic parallelepiped and the clinorhombic prism. The latter fits orthoclase better, as can be seen from Figs. 7*a* and 7*b*. According to Bravais, cleavage is parallel to the faces of greatest density, that is, those with molecules most closely packed. From the figures it can be seen that cleavage in orthoclase must be parallel to the {001}, {010}, and {110} forms, for the distance between adjacent rows of molecules is greatest for these directions.

The other feldspars evidently have almost the same structure as orthoclase. The separation parallel to the unit forms {110} and {1$\bar{1}$0} is cleavage rather than parting, though there may also be parting in the same direction in addition. Thus in the albite from Auburn, Me., and in oligoclase from New York City, the surfaces parallel to (110) and (1$\bar{1}$0) are coated with minute scales of sericite and the surfaces are rather dull.

SUMMARY

A peculiar intergrowth of microcline and albite is described. The albite plates are parallel to the unit prism faces. Plates parallel to (110) are in twinning position (albite twinning) with respect to the plates parallel to $(1\bar{1}0)$. The term perthite may be extended to include any regular intergrowth of albite with orthoclase or microcline, either of the latter being in excess (antiperthite when albite is in excess).



7*a*—Plan 7*b*—Side elevation

FIG. 7.—The space-lattice of orthoclase

Lamellar albite with easy planes of separation parallel to the side pinacoid {010} are explained by a parting in this direction. Here we have cleavage and parting in the same direction, and the variation in the side pinacoidal cleavage often noted in the literature may thus be explained.

Several kinds of plagioclase varying from albite to labradorite, and including $Ab_{12}An_1$, Ab_6An_1, Ab_3An_1, Ab_1An_1, and Ab_2An_3, show parting parallel to the rhombic section due to polysynthetic pericline twinning. The surfaces are dull and make slight angles with the cleavage surfaces. In these specimens we have examples of parting which are not parallel to either actual or possible crystallographic faces. As far as I know similar cases have not been recorded.

The imperfect separation in the feldspars parallel to the (110) and $(1\bar{1}0)$ faces is cleavage rather than parting. This cleavage is almost universally present and is of great assistance in orienting feldspar cleavages.

ROCK CLASSIFICATION ON THREE CO-ORDINATES[1]

ALEXANDER N. WINCHELL

There are many published classifications of igneous rocks, and their very number and variety are an indication of the difficulties inherent in the problem of constructing a satisfactory schematic arrangement—difficulties which are due largely to the fact that rocks are not chemical units, but mechanical mixtures, whose proportions may vary almost indefinitely in a great many ways.

It is generally admitted that at present the most satisfactory classifications are based upon, first, mineral (or chemical) composition, and, second, texture or geologic mode of occurrence. It is to be hoped that with advancing knowledge classifications may be based largely upon the principles of eutectics and the method of genesis of igneous types; at present the use of such conceptions as bases of classification may be recognized as desirable, but must be held in abeyance as impossible without more information.

A classification of igneous rocks based almost wholly upon chemical composition has been worked out in detail by Cross, Iddings, Pirsson, and Washington.[2] It has come into use gradually by an increasing number of petrologists, but its service to science is restricted by two facts: first, it commonly ignores the actual mineral composition in favor of an imaginary mineral composition known as the "norm," and, second, it cannot be used until the chemical composition[3] of the rock is known. Its great advantage lies in the fact that it reveals chemical characteristics and relationships with fidelity and clearness.

The classification of Rosenbusch,[4] which has been developed

[1] Published with the permission of the Director of the U.S. Geological Survey.

[2] *A Quantitative Classification of Igneous Rocks.* 1903.

[3] A microscopic determination of the quantitative mineral composition may be used as a substitute for a chemical analysis only when the norm and the mode are the same.

[4] *Elemente der Gesteinslehre.* 1910.

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	VOLCANIC	
ic, or ic	Felsitic, or porphyritic with dominant groundmass	Glassy
		Phonolitic: Obsidian, Pumice, Pitchstone, Perlite
TE	Phonolite	
ITE	Latite-phonolite	
ite	Tephrite	Tephritic: Scoria, Tachylyte
	Basanite	

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Peralkaline Igneous Rocks

			PLUTONIC	HYPABYSSAL: Aschistic	HYPABYSSAL: Felsic / Mafic	VOLCANIC	
Tex[ture]			Granitic	Porphyritic with coarse groundmass	Pegmatitic, aplitic or porphyritic	Felsitic, or porphyritic with dominant groundmass	Glassy
ALKALI FELDSPAR	Feldspathoid present	Soda-pyroxene, Soda-amphibole, Mica — Quartz	Nepheline-syenite	Nepheline-porphyry	TINGUAITE	Phonolite	Obsidian, Pumice (Phonolitic)
SODA-LIME FELDSPAR	Acid plagioclase with equal alkalifeldspar and feldspathoid	Pyroxene, Soda-amphibole, Mica — Quartz	Nepheline-monzonite	Nepheline monzonite-porphyry	ALLOCHETITE	Latite-phonolite	Pitchstone, Perlite
	Basic plagioclase with feldspathoid	Pyroxene, Soda-amphibole, Mica — Olivine	Theralite		Fourchite	Tephrite	Scoria, Tachylyte (Tephritic)
		+ Olivine	Olivine-theralite			Basanite	
NO FELDSPAR	No feldspathoid	Soda-pyroxene, Soda-amphibole, Mica — Olivine					
		+Olivine					

Trachydolerite

and modified by its author concurrently with [illegible] ent of petrography during the past [illegible] very wide usage, either in its author's own form [illegible] ed by geologists in some respects to [illegible] local needs. [illegible] ments of strength is the fact that [illegible] the mineral [illegible] sition, and only secondarily defined [illegible] n. It is also based upon the geologic [illegible] at the rocks of batholiths are separ [illegible] s and both are separated from [illegible] h has never put this classificatio [illegible] s fact has aided him in adapting [illegible] nabled him to employ in some gr [illegible] inor bases of divi [illegible] actors or properties wholly inapplicable [illegible] other groups.

It is surprising that even [illegible] h still recognizes geological age as [illegible] roups. He also emphasizes the imp [illegible] e and other rocks.

In spite of its relative inflexibility a diagrammatic or tabular scheme of classification has [illegible] h, for example, Kemp's[1] greatly simplified [illegible] busch classification owes much of [illegible] hemes have heretofore been arrang [illegible] ation-ships of rocks are so numer [illegible] of the chief defects of diagramm [illegible] ought out so few of these affiniti [illegible] paper such a classification may b [illegible] tes as shown on the triple insert, and the advantages of such [illegible] cheme obtained without the defec [illegible] three co-ordinates does not show [illegible] but it exhibits many more than [illegible] it is believed that no more can be shown without sacrificing the advan-tages of the tabular arrangement.

The classification given herewith is based largely upon that of Rosenbusch, but it differs fr [illegible] ortant respects, so that responsib [illegible] with the [illegible].

The first co-ordinate is in [illegible] r, and

[1] *Handbook of Rocks.* 1906.

Alkaline Igneous Rocks

				PLUTONIC	HYPABYSSAL		VOLCANIC	
					Aschistic	[illegible]		
		Texture		Granitic	Porphyritic with coarse groundmass	Pegmatitic, aplitic, or lamprophyric	Felsitic, or porphyritic with dominant groundmass	Glassy
ALKALI FELDSPAR	Soda-lime feldspar absent	Soda pyroxene, Soda-amphibole, Mica	+ Quartz	Alkali granite	Alkali granite porphyry	[illegible]	Alkali rhyolite	[illegible]
			− Quartz	Alkali syenite	Alkali syenite porphyry	[illegible]	Alkali trachyte	
SODA-LIME FELDSPAR	Acid plagioclase With equal alkalifeldspar	Pyroxene, Amphibole, Mica	+ Quartz	Quartz monzonite	Quartz monzonite porphyry	[illegible]	Quartz latite	
			− Quartz	Monzonite	Monzonite porphyry	[illegible]	Latite	[illegible]
	Basic plagioclase with little orthoclase or lenad	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	
			[illegible]	[illegible]			[illegible]	[illegible]
NO FELDSPAR	No feldspathoid	Soda-pyroxene, Soda-amphibole, Mica	− Olivine	Alkali pyroxenite			Augitite	
			+ Olivine	Alkali peridotite			Limburgite	

... or Alkalcic Igneous Rocks

...RUSIVE		HYPABYSSAL				VOLCANIC		
		Aschistic		Felsic / Mafic				
...c		Porphyritic with coarse groundmass		Pegmatitic, aplitic, or porphyritic		Felsitic, or porphyritic with dominant groundmass	Glassy	
...te	+Quartz	Nevadite	Pyroxene, Amphibole, Mica	PEGMATITE APLITE	Soda-lime feldspar present ALKALI FELDSPAR	Rhyolite Alkali-rhyolite	Rhyolitic	Obsidian
...te	—Quartz	Syenite-porphyry		SYENITE-APLITE Minette		Trachyte	Trachytic	Pumice
...te	+Quartz	Tonalite-porphyry	Amphibole, Mica	PLAGIAPLITE	Acid plagioclase	Dacite Quartz-latite	Dacitic	Pitchstone
...e	—Quartz	Esterellite		MALCHITE Kersantite	FELDSPAR	Andesite Latite phonolite	Andesitic	Perlite
...o	—Olivine	Gabbro-porphyry	Pyroxene	GABBRO-APLITE BEERBACHITE	Basic plagioclase SODA-LIME	Auganite Trachydolerite Tephrite		Scoria
...o	+Olivine	Olivine-gabbro-porphyry		...arewaite	Basic	Basalt Olivine-trachydolerite Basanite	Basaltic	Tachylyte
...e	—Olivine		Pyroxene, Amphibole, Mica		No feldspar NO FELDSPAR	Augitite (in part?) Augitite		
...e	Olivine					Picrite		

and modified by its author concurrently with the development of petrography during the past forty years, has come to have a very wide usage, either in its author's own form, or as modified by geologists in some respects to suit local needs. One of its elements of strength is the fact that it is based upon the mineral composition, and only secondarily defined in terms of chemical composition. It is also based upon the geological conditions of formation, so that the rocks of batholiths are separated from those of surface flows and both are separated from those of dikes and sills. Rosenbusch has never put this classification into diagrammatic form, and this fact has aided him in adapting it to advancing knowledge and enabled him to employ in some groups as minor bases of division factors or properties wholly inapplicable to other groups.

It is surprising that even in the latest form Rosenbusch still recognizes geological age as a basis of classification in some groups. He also emphasizes the important distinction between alkaline and other rocks.

In spite of its relative inflexibility a diagrammatic or tabular scheme of classification has numerous advantages, to which, for example, Kemp's[1] greatly simplified modification of the Rosenbusch classification owes much of its popularity. Such tabular schemes have heretofore been arranged on two co-ordinates. The relationships of rocks are so numerous and complicated that one of the chief defects of diagrammatic devices has been that they brought out so few of these affinities. By the use of transparent paper such a classification may be constructed on three co-ordinates as shown on the triple insert, and the advantages of such a scheme obtained without the defect mentioned. A classification on three co-ordinates does not show all the relationships that exist, but it exhibits many more than the ordinary arrangement, and it is believed that no more can be shown without sacrificing the advantages of the tabular arrangement.

The classification given herewith is based largely upon that of Rosenbusch, but it differs from the latter in various important respects, so that responsibility for it must lie with the author.

The first co-ordinate is in the direction normal to the paper, and

[1] *Handbook of Rocks.* 1906.

Normal or Alkalcic Igneous Rocks

				PLUTONIC	HYPABYSSAL		VOLCANIC		
					Aschistic	FELSIC Mafic			
Texture				Granitic	Porphyritic with coarse groundmass	Pegmatitic, aplitic, or porphyritic	Felsitic, or porphyritic with dominant groundmass	Glassy	
ALKALIFELDSPAR	Soda-lime feldspar present	Pyroxene, Amphibole, Mica	+Quartz	Granite	Nevadite	PEGMATITE APLITE	Rhyolite	Rhyolitic	Obsidian
			−Quartz	Syenite	Syenite-porphyry	SYENITE-APLITE Minette	Trachyte	Trachytic	Pumice
SODA-LIME FELDSPAR	Acid plagioclase	Amphibole, Mica	+Quartz	Tonalite	Tonalite-porphyry	PLAGIAPLITE	Dacite	Dacitic	Pitchstone
			−Quartz	Diorite	Esterellite	MALCHITE Kersantite	Andesite	Andesitic	Perlite
	Basic plagioclase	Pyroxene	−Olivine	Gabbro	Gabbro-porphyry	GABBRO-APLITE BEERBACHITE	Auganite		Scoria
			+Olivine	Olivine-gabbro	Olivine-gabbro-porphyry	Garewaite	Basalt	Basaltic	Tachylyte
NO FELDSPAR	No feldspathoid	Pyroxene, Amphibole, Mica	−Olivine	Pyroxenite			Augitite (in part?)		
			+Olivine	Peridotite			Picrite		

rocks belonging to a given series along this co-ordinate are placed within a single rectangle on successive sheets. For example, gabbro, essexite, and theralite form a series of this kind, the whole series to be observed simultaneously by looking through transparent paper for the second and third members. Along this co-ordinate igneous rocks are classified as normal or alkali-calcic (conveniently abbreviated to alkalcic), alkaline, and peralkaline.

Subsiliceous alkalcic rocks are characterized mineralogically by the absence of feldspars and feldspathoids and the presence of biotite, olivine, ferromagnesian (or mafic[1]), or calcareous-ferromagnesian (or calmafic), amphibole or pyroxene (or two or more of these). They are distinguished chemically by very low content of alkalies and alumina and high tenor of magnesia, lime, and iron. Mediosiliceous alkalcic rocks are characterized mineralogically by the presence of soda-lime feldspar nearly or wholly to the exclusion of alkali feldspar, and by the presence of biotite, olivine, mafic, or calmafic amphibole or pyroxene; they contain more soda than potassa (K_2O) and more than enough alumina to saturate the alkalies. Persiliceous alkalcic rocks are marked by the presence of soda-lime feldspar with dominant alkali feldspar, and with muscovite, biotite, or mafic or calmafic amphibole or pyroxene; chemically they are distinguished by the presence of both alkalies and lime with more than enough alumina to saturate the alkalies.

In general, alkalcic rocks are characterized by the presence of soda-lime feldspar (or no feldspar) with mica, olivine, mafic or calmafic amphibole or pyroxene, and the absence of feldspathoids (or lenads), soda-amphiboles, soda-pyroxenes, and lithia micas; they contain both alkalies and lime with more than enough alumina to saturate the alkalies.

Subsiliceous alkaline rocks are distinguished mineralogically by the absence of feldspars and lenads, and the presence of sodic and titaniferous amphiboles and pyroxenes; chemically they contain little alumina, and relatively large amounts of alkalies, titanic acid,

[1] The new terms felsic and mafic are here used in accordance with the proposal of Cross, Iddings, Pirsson, and Washington, *Jour. Geol.* XX (1912), p. 560, as short general terms, the first applying to feldspathic minerals and quartz, or rocks rich in such minerals, the second applying to all ferromagnesian minerals or rocks rich in such minerals.

and (often) ferric iron. Mediosiliceous alkaline rocks contain calcic plagioclase and a little lenad or alkali feldspar, and micas or soda-amphiboles or soda-pyroxenes; or they contain acid soda-lime feldspar with equal alkali feldspar and with micas, pyroxenes, amphiboles; chemically they contain in the first case high alkalies, lime, and titanic acid and low magnesia and silica, and in the second case high alkalies with potassa equal or dominant over soda, and abundant lime and alumina. Persiliceous alkaline rocks are characterized by dominant alkali feldspars, no soda-lime feldspar nor lenad, and lithia-mica, soda-amphibole, soda-pyroxene; they are very rich in alkalies and rarely in ferric iron, and very poor in lime and magnesia, and contain insufficient alumina to saturate the alkalies.

In general, alkaline igneous rocks contain sodic mafic silicates and no feldspar, or they contain more alkali feldspar and less soda-lime feldspar than the corresponding alkalcic rocks; chemically they contain more alkalies and less lime than the latter.

Peralkaline rocks are characterized mineralogically by the presence of feldspathoids (or lenads); they commonly contain also soda-pyroxene or soda-amphibole, or both. Chemically they are distinguished by insufficient silica to combine with the abundant alkalies to form feldspars after saturation of other available bases as orthosilicates.

In addition to the alkalcic, the alkaline, and the peralkaline, other divisions might be recognized, for example, the superalkaline, in which feldspars are entirely replaced by lenads. But this division consists of rocks which are very rare, and therefore it may be conveniently regarded as merely an extreme variation of peralkaline rocks. In spite of their rarity many names have been proposed for superalkaline rocks. Thus, by loss of feldspar, nepheline syenite becomes urtite, nepheline porphyry becomes sussexite, phonolite becomes leucitophyre, theralite changes to fergusite, tephrite to nephelinite or leucitite, olivine theralite to missourite, basanite to nepheline basalt or leucite basalt, and the volcanic equivalent of teschenite to analcite basalt. Another division might consist of the subsiliceous or lamprophyric rocks; but, with rare exceptions, such as shonkinite, the lamprophyric rocks are related

closely to gabbro, peridotite, or basalt, or their alkaline equivalents, and may be regarded as variations of such types.

The second co-ordinate extends from left to right across the paper and relates to mode of occurrence and conditions of formation; here again three classes are established, namely, plutonic, hypabyssal, and volcanic. Plutonic rocks solidified at considerable depth and have been later uncovered and brought to view through erosion. They form batholiths, stocks, and laccoliths. Hypabyssal rocks crystallized at moderate depth in the form of dikes, sills, or intrusions of irregular shape called chonoliths;[1] they are often called dike rocks. Volcanic rocks were brought to the surface (or near it) by volcanic action and form surface flows or intrusions near the surface. They also form beds and irregular aggregates through the accumulation of fragmental materials thrown out of volcanoes.

Plutonic rocks have granitic texture, that is, the essential constituents are crystalline anhedra of irregular shape and similar sizes, or dissimilar sizes showing gradations without a break from the smallest to the largest. Hypabyssal rocks may be divided into three types: the felsic, the aschistic, and the mafic. The aschistic or undifferentiated hypabyssal rocks commonly have porphyritic texture with abundant large phenocrysts and coarse granitic or aplitic groundmass. The felsic and mafic hypabyssal rocks commonly have aplitic texture, that is, they consist chiefly of fine evenly granular euhedral constituents, wholly crystalline. Some of these rocks have pegmatitic texture; others have porphyritic texture. The volcanic rocks commonly have glassy, felsitic, trachytic, or porphyritic textures; certain types have ophitic texture, in which the plagioclase feldspars in lath-shaped crystals are partly or wholly inclosed by mafic minerals.

The third co-ordinate extends from top to bottom of the sheet and relates to mineral composition; on this basis igneous rocks are divided into three primary groups: first, those in which alkali feldspar is dominant or in which felsic minerals including lenads are dominant, second, those in which soda-lime feldspar is equal to or dominant over alkali feldspar, or mafic minerals are equal to or

[1] R. A. Daly, *Jour. Geol.*, XIII (1905), 498.

dominant over felsic minerals including lenads, and, third, those containing no essential feldspar nor feldspathoid. Subdivisions are based largely upon quartz and olivine, since these minerals serve to measure the relative amount of silica present—the presence of quartz or the absence of olivine indicating a higher relative silication than the reverse condition.

It may be desirable to state explicitly that there are igneous rocks which will not readily find a place in this classification just as there are rocks which do not fit each other classification. Such a condition must exist, since rocks exhibit all sorts of gradations from one type to another, and classifications, on the other hand, establish sharply separated categories. A few illustrations will serve to emphasize this fact.

Rocks are classified as plutonic, hypabyssal, and volcanic, depending chiefly upon the depth at which they consolidate. But it is clear that there is a complete gradation in depth from the surface to the greatest depths open to observation. Similarly there is a gradation in the rocks formed at various depths. Hypabyssal rocks are found in dikes (or sills) consolidated at moderate depths. The same dikes may contain plutonic rocks at greater depths and volcanic rocks near the surface. Only those dike rocks which differ in some recognizable way from the plutonic and volcanic rocks are included as hypabyssal rocks.

Again, rocks are classified as alkalcic and alkaline. But there are many gradations from one type to the other. Granodiorite is an intermediate group of considerable importance. Assuming a total feldspar tenor of 60 per cent, Lindgren[1] has defined tonalite (or quartz diorite), as containing less than 8 per cent of alkali feldspar, granodiorite as containing 8–20 per cent of alkali feldspar, quartz monzonite, as containing 20–40 per cent of alkali feldspar, and granite as containing more than 40 per cent. The percentage of alkali feldspar cannot be accurately determined from an analysis of the rock because potassa (K_2O) may enter the plagioclase and soda may enter the orthoclase; it should be obtained by direct microscopic measurements. Granodiorite is intermediate between tonalite and quartz monzonite, and is therefore one of many con-

[1] W. Lindgren, *Amer. Jour. Science*, IX (1900), 269.

necting links between alkalcic and alkaline rocks. It is especially important because it constitutes large intrusions in California and elsewhere.

The volcanic equivalent of granodiorite, which may be appropriately called rhyodacite, forms another intermediate group between the alkalcic and the alkaline rocks. Having no distinctive name available, rhyodacites have been classed with dacites in the past; the two groups differ as distinctly as tonalite and granodiorite. It is because the rhyodacites and even some quartz latites have been described as dacites in the past that Daly[1] finds the average composition of dacite corresponding to that of granodiorite rather than tonalite. As may be seen from the tables of average composition of igneous rocks on pp. 217–221, dacite, like all the volcanic rocks, is more siliceous than the corresponding plutonic rock, tonalite, but is nevertheless its equivalent, as indicated especially by the tenor of alkalies. Similarly rhyodacite and granodiorite are related.

A rock which contains more ferromagnesian minerals (and less silica) than granite, but is nevertheless characterized by dominant alkali feldspar and quartz with subordinate plagioclase, has been called quartz syenite by Brogger.[2] It is sometimes regarded as intermediate between syenite and granite. But it is an alkaline and not an alkalcic rock type, and is very closely associated with quartz monzonite in the field. It should be regarded as a potassic variation from quartz monzonite, and not as a type closely related to granite. It is surprising to find that the average quartz syenite is less siliceous than the average quartz monzonite. This may be due to a tendency to classify the more siliceous quartz syenites as granites.

The relative depth at which rocks crystallized is estimated commonly by a study of their texture. Thus, plutonic rocks have granitic texture, volcanic rocks usually have felsitic or porphyritic texture; and textures are independent of mineral composition. But the ophitic texture, characterized[3] by the crystallization of

[1] R. A. Daly, *Proc. Amer. Acad.*, XLV (1910), 239.

[2] W. C. Brogger, *Zt. Kryst.*, XVI (1890), 81.

[3] A. N. Winchell, *Bull. Geol. Soc. Amer.*, XX (1908), 661.

plagioclase feldspars in lath-shaped forms before the solidification of the ferromagnesian minerals, is unknown in siliceous and ultrabasic rocks, and it is found in rocks crystallizing at moderate depth as well as in volcanic rocks. Independent of all other considerations, rocks having the ophitic texture are called diabase; they may occur in dikes or sills crystallizing at moderate depths, or they may be found in surface flows. Diabase proper has the mineral composition of augite andesite (or auganite); olivine diabase has the composition of basalt containing monoclinic pyroxene; quartz diabase and hypersthene diabase are also known.

The nomenclature employed is for the most part entirely familiar to petrographers. No distinction based on geological age is recognized; therefore such terms as melaphyre and quartz porphyrite are excluded. In designating the aschistic hypabyssal rocks the term porphyry is used (even for plagioclastic types) in preference to porphyrite. For the alkalcic plutonic and volcanic rocks it is believed that compound names like quartz diorite and augite andesite are objectionable, and should be replaced by simpler designations. Therefore, Spurr's[1] proposal to use tonalite in place of quartz diorite is adopted; and it is proposed to abbreviate augite andesite to the simple and almost self-explanatory form auganite.[2] Auganite proper is a volcanic rock consisting essentially of calcic plagioclase and augite; other varieties include hornblende auganite, related to andesite, and hypersthene auganite, which contains plagioclase and orthorhombic pyroxene with or without augite. A true augite andesite is a volcanic rock consisting essentially of sodic plagioclase (andesine or oligoclase) and augite.

That auganite deserves a distinctive name and is not merely a variety of andesite, as suggested by the name augite andesite, is well shown by field relations such as those existing at National, Nevada, where the important rocks are rhyolite, andesite, and auganite. At this locality the auganite and andesite are of wholly different age and wholly different appearance. The auganite might be confused with basalt without close examination, since it

[1] J. E. Spurr, *Amer. Geol.*, XXV (1900), 210, 232; *U.S. Geol. Surv. 20th Ann. Rpt.*, VII (1900), 188, 190.

[2] A. N. Winchell, *Mg. and Sci. Press*, November 22, 1912.

is black and dense; but its separation from the andesite is accomplished at a glance when both rocks are fresh.

A substitute for the compound name olivine gabbro is desirable but is not here suggested.

The average composition of each type of igneous rock should be available for comparison with the composition of rocks at given localities. Daly[1] has prepared tables giving these averages for certain rock types; in the following tables these have been supplemented by averages computed by the author.

In the tables of average composition, numbers 1, 4–7, 10, 13, 16, 19, 21, 23, 25, 26, 31–34, 36, 38, 40, 49–52, 54–57 were calculated by Daly;[2] the others have been prepared from data published by Rosenbusch (*Elemente der Gesteinslehre*, 3d edition, Stuttgart, 1910), and by Clarke (*U.S.G.S. Bulletin 419*, 1910), with the following exceptions. No. 3 is based on data of Rosenbusch (*loc. cit.*), Clarke (*loc. cit.*), and Osann (*Chemische Petrographie*, II, 1905). No. 9 is from data of Rosenbusch (*loc. cit.*), Clarke (*loc. cit.*), Osann (*loc. cit.*), and Weidmann (*Wis. Surv. Bull. XVI*, 1907). No. 14 is based on data of Rosenbusch (*loc. cit.*), Washington (*Jour. Geol.*, VII [1899], 57), and Ogilvie (*Jour. Geol.*, XVI [1908], 285). No. 15 is based on data of Rosenbusch (*loc. cit.*) and Osann (*loc. cit.*). No. 17 is from data of Rosenbusch (*loc. cit.*), Lacroix ("Minéralogie de Madagascar," *Nouv. Arch. Muséum*, I [1903], 30, 194), and Young (*Geol. Surv. Canada*, XVI, H, 1906). No. 27 is from data of Rosenbusch (*loc. cit.*) and Hore (*Econ. Geol.*, VI [1911], 54). No. 29 is from data of Rosenbusch (*loc. cit.*) and Doelter (*Akad. Wiss. Wien*, CXI, I [1902], 980). No. 37 includes 12 quartz keratophyres (Daly), 13 pantellerites (data of Rosenbusch), and 6 comendites (data of Rosenbusch). No. 44 is from data of Daly (*loc. cit.*), Clarke (*loc. cit.*), Rosenbusch (*loc. cit.*), and Osann (*loc. cit.*), auganites excluded. No. 47 is from data of Clarke (*loc. cit.*), Rosenbusch (*loc. cit.*), and Osann (*loc. cit.*), rocks containing acid plagioclase or orthoclase being excluded.

[1] R. A. Daly, *Proc. Amer. Acad.*, XLV (1910), 211.

[2] *Loc. cit.*

AVERAGE COMPOSITION OF PLUTONIC ROCKS

	1 Granite	2 Alkali-granite	3 Syenite	4 Alkali-syenite	5 Nepheline Syenite	6 Tonalite	7 Granodiorite	8 Quartz Monzonite	9 Quartz Syenite	10 Diorite	11 Monzonite	12 Nepheline Monzonite
No. of analyses	236	10	13	23	43	20	12	25	18	70	10	1
SiO_2	69.92	72.70	58.06	61.99	54.63	59.47	55.10	65.78	62.34	56.77	55.3[illegible]	46.40
Al_2O_3	14.78	12.12	16.25	17.93	19.89	16.52	15.82	15.71	15.06	16.67	15.91	21.60
Fe_2O_3	1.62	2.28	4.18	2.22	3.37	2.63	1.64	1.83	2.32	3.16	3.25	4.07
FeO	1.67	1.44	3.48	2.29	2.20	4.11	2.66	2.22	3.02	4.40	4.02	4.95
MgO	.97	.32	2.52	.96	.87	3.75	2.17	1.57	2.76	4.17	4.33	2.75
CaO	2.15*	.49	4.06†	2.55	2.51	6.24	4.66	3.76	3.98‡	6.74	6.86	8.44
Na_2O	3.28	5.42	3.67	5.54	8.26	2.98	3.82	3.35	3.56	3.39	3.73	6.29
K_2O	4.07	4.20	5.16	4.98	5.46	1.93	2.29	3.80	4.68	2.12	4.18	2.71
H_2O	.78	.82	1.37	.76	1.35	1.39	1.09	1.17	1.09	1.36	.67	1.25
TiO_2	.39	.09	.63	.56	.86	.64	.54	.53	.74	.84	.73	1.57
P_2O_5	.24	.12	.39	.14	.25	.26	.16	.18	.21	.25	.46	.26
MnO	.13	......	.23	.08	.35	.08	.05	.10	.24	.13	.11	......
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.29

* Includes 0.02 SrO and 0.06 BaO. † Includes 0.11 SrO and 0.15 BaO. ‡ Includes 0.10 SrO and 0.34 BaO.

AVERAGE COMPOSITION OF PLUTONIC ROCKS—*Continued*

	13 Gabbro	14 Essexite	15 Theralite	16 Olivine Gabbro	17 Olivine Essexite	18 Olivine Theralite	19 Pyroxenite	20 Alkali-pyroxenite	21 Peridotite	22 Alkali-peridotite	
No. of analyses	24	6	4	17	6	2	4	3	49	1	
SiO_2	49.50	49.92	48.95	46.49	46.44	41.45	49.82	44.30	44.39	28.15	......
Al_2O_3	18.00	18.59	15.45	17.73	19.27	14.94	5.12	8.93	5.14	2.30	......
Fe_2O_3	2.80	4.19	3.97	3.66	3.85	7.76	1.83	7.94	3.88	21.61	......
FeO	5.80	5.01	4.63	6.17	6.02	7.72	7.44	7.75	6.70	15.93	......
MgO	6.62	2.66	5.24	8.86	4.33	6.11	19.55	10.29	29.17	20.67	......
CaO	10.64	7.32	10.70	11.48	8.65	10.44	13.00	15.28	6.13	3.45	......
Na_2O	2.82	5.67	4.30	2.16	4.90	5.69	.37	.74	.64	.63	......
K_2O	.98	3.05	2.29	.78	2.34	2.42	.21	1.05	.76	.29	......
H_2O	1.60	.91	2.21	1.04	1.18	1.51	1.06	1.18	1.80	3.45	......
TiO_2	.84	1.76	1.52	1.17	2.10	1.61	1.46	2.31	.88	2.55	......
P_2O_5	.28	.80	.47	.29	.81	.35	.05	Tr.	.14	Tr.	......
MnO	.12	.22	.17	.17	.11	......	.09	.23	.19	.45	......
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.98	100.00	......

AVERAGE COMPOSITION OF HYPABYSSAL ROCKS

	Felsic Types								Mafic Types				
	23 Aplite	24 Alkali-aplite	25 Bostonite	26 Tinguaite	27 Plagi-aplite	28 Malchite	29 Allochetite	30 Beerbachite	31 Minette	32 Kersantite	33 Camptonite	34 Fourchite (and Monchiquite)	35 Garewaite
No. of analyses	15	6	5	15	10	6	2	1	10	20	15	16	1
SiO_2	75.00	74.40	61.32	55.02	68.75	60.18	50.19	47.21	49.45	50.79	40.70	45.17	42.84
Al_2O_3	13.14	13.11	18.43	20.42	16.36	17.81	22.40	20.52	14.41	15.26	16.02	14.78	4.60
Fe_2O_3	.58	.96	3.84	3.06	.78	1.38	3.03	7.48	3.39	3.29	5.43	5.10	5.69
FeO	.40	1.10	1.60	1.82	1.57	4.21	3.60	5.32	5.01	5.54	7.84	5.05	8.48
MgO	.30	.07	.46	.59	.63	2.92	1.95	4.16	8.26	6.33	5.43	6.26	24.60
CaO	1.13	.30	1.45	1.67	2.60	5.37	5.26	8.63	6.73	5.73	9.36	11.06	11.41
Na_2O	3.54	4.55	5.75	8.63	7.24	4.14	6.85	5.17	2.54	3.12	3.23	3.69	.61
K_2O	4.80	5.12	4.94	5.38	.68	2.56	3.40	.33	4.69	2.79	1.76	2.73	.42
H_2O	.71	.21	1.31	2.77	1.06	.65	2.46	.34	3.04*	5.71†	5.59‡	3.40	1.80
TiO_2	.30	.18	.89	.36	.28	.42	.86	.....	1.23	1.02	3.86	1.90	.....
P_2O_5	.05	Tr.	.....	.06	.05	.17	.....	.46	1.12	.35	.62	.51	.....
MnO	.07	Tr.	.01	.22	Tr.	.19	.....	.....	.13	.05	.16	.35	Tr.
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	99.91	100.00	100.00	100.00	100.00	100.45

* Includes 0.61 CO_2. † Includes 2.61 CO_2. ‡ Includes 2.97 CO_2.

AVERAGE COMPOSITION OF VOLCANIC ROCKS

	36 Rhyolite	37 Alkali-rhyolite	38 Trachyte	39 Alkali-trachyte	40 Phonolite	41 Dacite	42 Rhyodacite	43 Quartz Latite	44 Andesite	45 Latite	46 Latite-Phonolite
No. of analyses	64	31	48	17	25	16	16	6	57	18	6
SiO_2	72.60	72.72	60.68	62.46	57.45	65.86	67.67	65.81	61.30	57.93	56.82
Al_2O_3	13.88	11.68	17.74	17.13	20.60	15.64	15.62	16.72	16.88	17.05	19.09
Fe_2O_3	1.43	3.09	2.64	2.89	2.35	2.56	2.00	3.10	3.01	3.88	2.81
FeO	.82	1.43	2.62	1.92	1.03	1.70	1.25	.55	2.76	2.66	2.06
MgO	.38	.35	1.12	.53	.30	1.71	.76	.66	2.49	2.13	1.19
CaO	1.32	.80	3.09	1.43	1.50	4.24	2.56	2.88	5.07	5.16*	4.10
Na_2O	3.54	5.66	4.43	6.30	8.84	3.93	4.10	3.73	3.99	4.19	6.67
K_2O	4.03	3.10	5.74	5.36	5.23	1.90	3.73	4.28	1.89	4.13	4.79
H_2O	1.52	.62	1.26	.97	2.04	1.77	1.61	1.52	1.33	1.52	1.18
TiO_2	.30	.23	.38	.61	.41	.47	.48	.43	.86	.87	.84
P_2O_5	.06	.08	.24	.15	.12	.14	.15	.17	.25	.40	.30
MnO	.12	.24	.06	.25	.13	.08	.07	.15	.17	.08	.15
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

* Includes 0.15 BaO.

AVERAGE COMPOSITION OF VOLCANIC ROCKS—*Continued*

	47 Auganite	48 Trachy-dolerite	49 Tephrite	50 Diabase	51 Olivine Diabase	52 Basalt	53 Olivine Trachy-dolerite	54 Basanite	55 Augitite	56 Picrite	57 Limburgite
No. of analyses..	73	10	24	20	17	161	27	16	6	3	7
SiO_2..........	54.97	50.93	49.14	50.12	50.10	48.78	48.74	44.20	42.25	43.24	41.69
Al_2O_3..........	16.69	19.06	16.57	15.68	14.43	15.85	16.41	15.64	16.26	15.19	14.80
Fe_2O_3..........	3.94	4.49	3.65	4.55	5.06	5.37	4.62	4.35	8.43	8.62	15.04
FeO..........	4.75	3.88	6.68	6.73	6.31	6.34	6.26	6.14	5.46	7.89	
MgO..........	4.13	2.72	3.98	5.85	7.32	6.03	4.29	8.89	5.49	8.56	8.64
CaO..........	8.02	7.04	9.88	8.80	9.53	8.91	8.06	9.74	9.75	13.78	11.98
Na_2O..........	3.19	4.91	2.57	2.95	2.75	3.18	4.08	4.03	4.45	.54	3.52
K_2O..........	1.45	3.47	3.39	1.38	.73	1.68	2.83	1.83	1.92	.48	1.17
H_2O..........	1.39	1.80	2.00	1.93	2.00	1.76	1.77	2.67	2.43	1.21	2.36
Ti_2O_2..........	.89	.74	1.00	1.41	1.25	1.39	1.85	1.64	2.52	.....	.67
P_2O_5..........	.28	.65	.84	.37	.27	.47	.80	.68	1.04	.49	.13
MnO..........	.30	.31	.30	.23	.25	.29	.29	.19	.....	.....	.....
	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

It should be remembered that rock names are not always used with the same meaning; therefore some of the averages presented herewith include analyses of rocks not classified in accordance with recent practice; this is especially true of the average for granite, which certainly includes some analyses of rocks which would now be classified as quartz monzonite, and probably includes also a few alkaligranites. The average for basalt probably includes analyses of trachydolerites. It is to be hoped that averages for these rocks will be prepared from analyses of rocks whose correct classification cannot be questioned.

If the average quantitative mineral composition of the various igneous rocks were known, it would be as useful as the average chemical composition. Of course the "normative mineral composition" can be calculated directly from the average chemical composition for each rock type. But the "normative mineral composition" is much less important than the "modal" mineral composition; it is merely the result of a distribution of the oxides among a certain group of minerals somewhat arbitrarily selected. In a few cases the actual (modal) mineral composition can be calculated at least approximately from the chemical composition. As our knowledge of the composition of the mineral constituents of each rock type increases, the mineral composition can be calculated for an increasing number of rocks.

A few calculations of this kind have been made; they are much facilitated by the use of Mead's circular slide rule.[1] For the alkaligranite all the ferric iron is assigned to riebeckite; alkaligranites often have, in place of riebeckite, either arfvedsonite, acmite, barkevikite, lithia mica, or two or three of these minerals. All the magnesia of the quartz monzonite is assigned to biotite and hornblende (including augite) in the ratio (about 3 to 1) required to prevent surplus of either lime or alumina in forming feldspars. The biotite and hornblende are assumed to have the composition obtained by analysis of those minerals from quartz monzonite from California (analysis *d*, Table XIV, and *a*, Table XIII, *Quant. Class. Ign. Rocks*). In calculating the mineral composition of the monzonite sufficient magnesia is assigned to biotite and hornblende to prevent

[1] W. J. Mead, *Econ. Geol.*, VII (1912), 136.

either an excess or a deficiency of silica in forming pyroxene. The biotite and hornblende are assumed to have the composition obtained by analysis of such minerals from monzonite (analysis *c*, Table XIV, and *b*, Table XIII, *Quant. Class. Ign. Rocks*).

As a preliminary, it is necessary to calculate the mineral composition in terms of the theoretical feldspar molecules; these may be changed into the feldspars actually present as follows. The feldspar of alkaligranite is either anorthoclase or perthitic albite with microcline or orthoclase. The second condition needs no further calculation; the first condition is obtained by simply combining the calculated orthoclase and albite. Andesine is the commonest plagioclase of quartz monzonite and monzonite; assigning to it the formula Ab_3An_2 the calculation results as follows:

APPROXIMATE AVERAGE MINERAL COMPOSITION OF ALKALI-GRANITE, QUARTZ MONZONITE, AND MONZONITE

	1 Alkaligranite	2 Quartz Monzonite	3 Monzonite
Quartz	24.7	23.7	....
Orthoclase	24.7	....	....
Albite	38.7	....	....
Soda-orthoclase	....	24.4	33.9
Andesine Ab_3 An_2	....	36.2	34.0
Riebeckite	8.5	....	....
Ferriferous diopside	2.1	....	....
Pyroxene	....	3.1	18.8
Hornblende	....		3.2
Biotite	....	9.1	2.5
Magnetite	....	1.8	4.3
Ilmenite	0.2	....	....
Titanite	....	0.6	1.4
Apatite	0.3	0.4	1.1
(Water)	0.8	0.7	0.8
	100.00	100.00	100.00

THE OLD EROSION SURFACE IN IDAHO

A REPLY

JOSEPH B. UMPLEBY[1]

In a recent issue of this *Journal*[2] Mr. Eliot Blackwelder criticizes adversely the chain of reasoning that led me to the conclusion that the old erosion surface in Idaho is of Eocene age. To him the evidence seems to point to a much younger age, "probably post-middle-Miocene"—an inference which I believe to be incompatible with observed facts.

To account for the valleys now filled in many places with lavas, lake beds, and fluviatile deposits principally of Miocene age, Mr. Blackwelder suggests three possible explanations.

> One method is the deposition of the sediments in the bottoms of the valleys, in essentially their present state, as suggested in the [original] article. Again where weak materials have been down-folded or down-faulted between masses of harder rocks, they may be eroded to a lowland on account of differences of resistance to denuding processes. A third hypothesis is that the broad valleys occupied by the sediments were excavated and filled before the peneplain was made.

I shall endeavor to show that the first hypothesis only accords with field evidence. The second hypothesis is inadmissible because the old valleys constitute branching systems with members lying athwart the structure axes of the region. To derive all of these valleys by faulting would be to assume a complexity of fault systems in no wise borne out by field observations. Again, some of the lakes of Miocene age, as shown by fossil plants, present shore lines at elevations 2,800 feet beneath the plateau surface, so that even if down-faulting could be admitted the valleys in which the lakes existed must have been blocked out prior to the lacustrine epoch and hence prior to the Miocene. Therefore if the plateau

[1] Published with the permission of the Director of the United States Geological Survey.

[2] *Jour. Geol.*, XX, No. 5 (1912), 410–14.

surface is a product of planation it must antedate the existence of such Miocene lakes.

Still another line of evidence against the down-faulting or down-folding hypothesis is the direct observation from numerous exposures that folding or faulting is rare along the margins of the old valleys. In many places present-day streams have cut vertically from 1,000 to 3,000 feet or more into the lavas and tuffs which occupy the old valleys and thus afford excellent cross-sections of the earlier drainage channels. In the many sections of this kind which were examined, only one (near Junction, Lemhi County, and here the fault is post-Miocene) showed evidence of faulting and none presented down-folding. The eruptive rocks or lake beds, usually in a nearly horizontal position, abut the older formations irrespective of their attitude and in many places the lavas contain fragmental material, clearly picked up from the surface over which they flowed. Furthermore, the slope of the contact in every place observed is toward the lava area.

The third hypothesis, which supposes that the valleys antedate the old erosion surface, is controverted by the shore-line relations already referred to. If the valleys were developed *before* the elevation of the old surface of gentle topographic forms, we are led directly to the conclusion that within the area planated the upper 2,800 feet of some of the old valleys remained unfilled throughout the period of that planation. Would not those portions below base-level have been filled, and that, early in the period of reduction?

The third hypothesis is also untenable in view of the inequal depth of the lavas along certain of the old valleys. Take, for instance, the one which extends from near Salmon City, via Prairie Basin, Rabbitfoot, Custer, and Stanley Basin, to the Snake River plains at Camas Prairie. Prairie Basin, about 1,000 feet below the plateau level, Stanley Basin, about 2,500 feet below it, and Camas Prairie, yet lower, represent unfilled segments of this old valley, while intermediate sections are flooded with lavas which in places, as at Twin Peaks in Parker Mountain mining district and at Estes Mountain near Custer, rise a few hundred feet above the plateau level.

Furthermore, the third hypothesis is untenable because of the topography along certain of the present-day streams. Salmon River heads in the Stanley Basin segment of the old valley above mentioned but near Stanley leaves it and enters a canyon so narrow that there is scarcely room for a wagon road. This gorge continues to a point near Challis, a distance of about 50 miles, where the stream emerges into a broad, open depression. Fifteen miles below Challis the river enters another narrow canyon which it follows for about 30 miles to a point near Salmon City, and, after flowing for 20 miles through a third broad valley, again enters a gorge which it follows nearly to the western border of the state. These open stretches along the course of Salmon River cannot be explained by local structure or by differences of resistance to denuding processes. Their distribution and individual outline are readily interpreted, however, if we consider them to be parts of the older valley system. The general depression about Challis has its greatest elongation almost at right angles to the course of Salmon River, but is itself continuous with an old valley, now filled in many places with eruptive rocks, which drained off to the southeast and joined the Snake River plains near Martin. The open stretch about Salmon City presents numerous exposures of plant-bearing Miocene lake beds which extend off to the southeast along the present course of Lemhi River and Birch Creek. To an observer in the field it is very clear that these open stretches date back to the earlier topography and that, though in part filled with Miocene lavas and sediments, they have persisted as great depressions throughout their entire history.[1] Salmon River has crossed them by headward erosion.

In the preceding paragraphs I have endeavored to show (1) that the old valleys were not developed by down-folding or down-faulting and (2) that they were not excavated prior to the planation of the region. The remaining hypothesis holds that the valleys are the product of erosion and were developed after the elevation of the old

[1] During the past three field seasons many notes have been made on the old valleys of southeastern Idaho north of Snake River, and several hundred miles of their courses have been sketched. It is expected to assemble this information in a later paper.

erosion surface. This is the view which I advanced in my original paper and to which I still subscribe.

The inequal filling of the old valleys, their branching systems with members athwart the structure axes of the region, their cross-sections, the absence of particular folding or faulting along their margins, the shore-line relations of the lakes which occupied some of them in Miocene times, the open stretches along the present drainage lines—all these features stand opposed to the second and third hypotheses but at the same time strongly support the first one.

The constructive part of Mr. Blackwelder's criticism is based on the third hypothesis; namely, that the old valleys, now in part filled with Miocene deposits, were formed *before* the period of profound degradation which resulted in the old erosion surface of Idaho. The fact that in many of the valleys the filling material never accumulated to within many hundreds of feet (2,800 feet at Salmon City and Gilmore) of the present plateau surface, is not easy to explain on the basis of this assumption. Widely distributed, deep depressions could not have persisted within the area during the period of its reduction to gentle topographic forms.

Mr. Blackwelder also objects to my belief that the old valleys were formed during the Oligocene epoch. I am well aware of the uncertainties involved in "allowing a geologic period for a process of unknown time requirements," but it does seem that in this case time requirements are as well known as is the duration of the geologic period involved. The coincidence of the Oligocene epoch with the development of the old valleys is not considered as an essential part of the constructive argument in my former paper, but is rather a corroborative bit of evidence. A considerable time must have been consumed in the development of these great valleys, especially so since they lie far within the plateau area. If the drainage was westward, as is suggested in a later paragraph, the streams must have worked headward, at least across the state of Idaho. This follows from the fact that the plateau is continuous to near the western border of the state. Limits are placed on the period of valley development on the one hand by the Miocene deposits which occupy them, and on the other by the old erosion

surface, thought to be of Eocene age because of its relation to surrounding Eocene sediments. The closing stages of the Eocene may have been involved in the development of the old valleys, although I do not think so, but that erosion continued locally within them on into the Miocene and somewhat intermittently, even down to the present, is attested by abundant evidence. Such facts and possibilities, however, do not appear to me to affect the conclusion that the old valleys, here filled and there partially filled, are parts of a drainage system which should be considered as Oligocene.

The latter part of Mr. Blackwelder's paper is devoted to an effort to show that the old erosion surface "is much younger than Eocene and probably post-middle-Miocene." In the earlier part of this reply I have emphasized the fact that the deep erosion valleys were locally never filled by many hundreds of feet with Miocene or other lavas or sediments, and hence could not have been formed until after the old surface of gentle topographic forms had been developed, and not until after it was elevated at least well toward its present position. The hypothesis that the valleys were developed prior to the planation of the region necessitates that they persisted throughout the period of that planation and at its close remained as open trenches, some of them 2,800 feet deep, in an area which approached closely the base-level of erosion for the region.

Mr. Blackwelder's principal evidence for his contention that the old surface is of late Miocene age is the general folding which the Miocene deposits of the region have undergone—a folding which he argues would have destroyed the evenness of the plateau surface. The folding of the lacustrine deposits has been brought to my attention by numerous exposures in Lemhi and Custer counties. About Salmon City the lake beds, which, from their thin-bedding, must have been laid down in a relatively horizontal position, are now inclined in various directions, in most places at angles of about 10 degrees, but locally they dip as steeply as 25 degrees. It is noteworthy, however, that the dips, in every instance where I have observed them, change direction within short distances. The disturbance which folded these lake beds and locally faulted them, also folded and faulted the plateau surface, hence my statement

that "faulting and folding have affected the plateau area of central and eastern Idaho since its last elevation" but it has not destroyed its plateau character and "through all, the integrity of the old surface has persisted in a remarkable degree." From Salmon City to Gilmore, a distance of about 90 miles, the shore-line of the Miocene lake rises from 5,700 to 7,200 feet above sea, and along the same traverse the summits rise from 8,500 to 10,000 feet. Within this general rise to the southeast, however, are several subordinate anticlines and synclines.

A surface determined by the combined crestlines of the region would be "an undulating plain" dipping gently to the northwest and not a surface with maximum "declivities of but a small fraction of one degree" as Mr. Blackwelder seems to conceive it.

The casual reference which Mr. Blackwelder makes to the Payette formation as of late Eocene age, though not followed to its logical conclusion by him, touches upon what I believe to be the only essential weakness in my earlier paper. If the Payette formation is really of late Eocene age, either it must have been deposited in a different physiographic province or the old erosion surface must be crowded back, probably into the Cretaceous. I believe that the valley occupied by the Payette formation has a history coincident with the several valleys which I have studied—in fact that they are tributary to it. Near Hailey Mr. Lindgren found lacustrine deposits which, from their relations to the lavas and also from floral remains (*Sequoia angustifolia*), he believed to be Payette.[1] I have visited the Hailey locality and feel sure that the beds here mapped occupy a valley tributary to the one which earlier in this paper is described as extending from Camas Prairie nearly to Salmon City. I. C. Russel,[2] in his studies of the Snake River plains, was led to infer that the Payette formation extended eastward beneath the lavas—an inference supported by the relation of the plains to several of the old valleys which I have visited. From these observations it seems probable that the Payette formation, the lake beds at Salmon City, those at Challis, and the

[1] Waldemar Lindgren, *Twentieth Ann. Rept. U.S. Geol. Survey*, Pt. III (1898–99), p. 197.

[2] I. C. Russel, *Bull. U.S. Geol. Survey 199* (1902), p. 51.

several belts of lava in east-central Idaho all occupy valleys developed by streams of the same river system. Of these several beds, which from their topographic relations may reasonably be thought to be of about the same age, all have been referred to the Miocene except the Payette formation. In view of this fact it may be pertinent to review briefly our knowledge of the age of the Payette formation.

The Payette formation was first assigned to the Miocene,[1] but later because of a change in the reference of the deposits of Bridge Creek, Ore., which, in addition to a somewhat similar flora, have yielded vertebrate remains, it was shifted to the Eocene.[2]

The correlation of the Payette formation with the deposits of Bridge Creek is based on six species of plants which they have in common. The Payette flora, however, "embraces 32 forms, of which 17 were described as new and 5 were not specifically named, leaving, as then known [the first report] only 10 species having an outside distribution." Five of these were found at Bridge Creek "and to this list I am now able to add another species, thus making 6 of the 10 species common to these two localities."[3]

The other lake beds of the plateau region have not as yet yielded nearly as varied a flora as the Payette but it is hoped that additional search in the near future will add greatly to the collections from them. It is possible that during the next field season one of the paleobotanists of the United States Geological Survey will devote considerable time to this problem.

The only change which such studies may make in the age of the old erosion surface as now defined is to crowd it back toward or into the Cretaceous. This would result if the several localities yielded definite Eocene plant remains. The principal reason for my belief that such a change will not be made is expressed in my first paper as follows:

> It seems that the [surrounding Eocene] sediments could not have been derived from the region after its last elevation for two reasons: (1) It is very doubtful if the plateau is sufficiently dissected to afford the volume of material

[1] Waldemar Lindgren, *Twentieth Ann. Rept. U.S. Geol. Survey*, Pt. III (1900), 95.

[2] F. H. Knowlton, *Bull. U.S. Geol. Survey No. 204* (1902), p. 110.

[3] *Ibid.*, p. 110.

represented by the Eocene beds, and (2) all the more important valleys of the area drain westward, and in all probability have done so throughout their entire history. This is true of the Rocky Mountain trough, the Purcell trough, and the Snake, Salmon, and Columbia river channels. These, together with their tributaries, represent perhaps 90 per cent of the present dissection of the plateau region. If we assume that the old erosion surface is pre-Eocene the material derived from these several valleys may be thought to account for the narrow fringe of Eocene sediments on the west, but cannot account for the incomparably more extensive Eocene beds that lie to the east of the present plateau region.

In conclusion, I cannot agree with Mr. Blackwelder that "the evidence seems to show that this peneplain is much younger than Eocene and probably post-middle-Miocene." The evidence to me seems decisive that the plateau surface of the present day is much older than the late-Miocene. If it is other than Eocene, as concluded in my earlier paper, I believe that it must, because of evidence herein set forth, be crowded back toward or into the Cretaceous. Individual lines of evidence for assigning the old erosion surface of Idaho to the Eocene may not be conclusive but since all lines of approach, so far as I have been able to analyze them, point without discord[1] in the same direction, it seems to me that the assignment must be correct, and it is firmly believed that the surface does form a "valuable datum plane in broad areas where time relations between the Algonkian and the Pleistocene are otherwise obscured."

[1] Except the assignment of the Payette formation to the Eocene, as discussed above.

NOTES ON THE ORIGIN OF CERTAIN PALEOZOIC SEDIMENTS, ILLUSTRATED BY THE CAMBRIAN AND ORDOVICIAN ROCKS OF CENTER COUNTY, PENNSYLVANIA

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During the Cambrian period the North American continent subsided relative to sea-level. Before the close of the period epicontinental seas had transgressed the greater part of the continent now included within the borders of the United States, and, through the Upper Cambrian at least, limestone-forming conditions prevailed somewhat extensively in the central and southern Appalachian region. Whether this apparent subsidence was due to diastrophic movements or to the more or less complete base-leveling of Cambrian continental areas is not altogether certain. The type of sediments accumulated during Lower and Middle Ordovician time suggests that it was due to base-leveling rather than to diastrophism. In this central and southern Appalachian region great thicknesses of limestones accumulated between the Upper Cambrian and Trenton beds. Clastic sediments are sparsely represented and those which are present are peculiar in character. Yet land areas could not have been very far distant to the east and northeast, because in adjacent states this very time interval is represented by an unconformity and period of erosion, as for example in New Jersey.[1] The most reasonable explanation then seems to be that the adjacent land area had been reduced during the Cambrian to a peneplain. As a result, the streams and rivers did not have sufficient velocity to transport any considerable amount of clastic material into the adjacent epicontinental sea. Weathering processes, however, were at work and a thick mantle of residual rock waste was being prepared all over the peneplained land surface, only waiting for renewed stream activity to be

[1] Weller, *Geol. Surv. N.J., Report on Pal.*, III (1903), 15.

carried away. The soluble constituents, on the other hand, and particularly the lime carbonate, were being carried away in solution. This furnished the material for the thick calcareous deposits of early Ordovician time.

After this calcareous material was carried to the sea, the question arises as to how it was separated from solution and deposited as limestone. Marine animals could have done the work, but these deposits are strikingly unfossiliferous except at very widely separated horizons, and there are many peculiarities of the rock which cannot be explained upon this basis. Chemical precipitation has been suggested as a possible explanation, but this, too, is inadequate, as will be presently shown. The object of the present paper is to outline the probable course of events in Upper Cambrian and Lower Ordovician time which, it is thought by the author, will best explain the origin of these deposits and some of the peculiar physical characters which they now possess. The observations and deductions here recorded are largely based on field investigations carried on in the vicinity of Bellefonte and State College, Center County, Pa.

Rocks ranging in age from the Upper Cambrian through the Ordovician are exposed in an unsymmetrical eroded anticline which extends in a northeast-southwest direction across the Bellefonte quadrangle between the Bald Eagle Mountains on the northwest and Nittany Mountain on the southeast. This anticline pitches toward the northeast. Its northwestern limb is generally almost vertical and in some places even overturned by a few degrees. The southeastern limb, on the other hand, has very gentle dips, generally ranging from 8 to 15 degrees.

The lowest beds exposed are composed of limestone of variable character containing *Cryptozoon proliferum* in abundance and trilobites of Upper Cambrian age, the latter limited to thin fossiliferous layers. The fossiliferous layers are frequently oölitic and other oölitic layers occur. In addition to these, occasional layers of a peculiar conglomerate are found. This conglomerate is composed of broad, thin pebble-like structures ranging from half an inch or less up to three or four inches in diameter, and generally less than half an inch thick. The edges are rounded, the outline

circular, oval, or irregular, and the individual pebbles are either flat or rarely curved. They occur in the conglomerate closely packed together and in all positions relative to the bedding planes, flat, edgewise, or inclined. The frequency with which these broad, thin pebbles occur on edge has given rise in certain localities to the name "edgewise" conglomerate.[1]

Above these Cambrian limestones come a series of apparently unfossiliferous interbedded sandstones and limestones several hundred feet thick and very peculiar in character. The sandstones are composed of pure white quartz sand, extremely well rounded, and loosely cemented together by calcareous or dolomitic cement. Ordinary weathering conditions quickly remove this cement and the rock yields a thick mantle of sandy soil poorly adapted to agricultural purposes. On account of this character the region is locally known as the barrens. The interbedded limestones are of a peculiar character also. They are unfossiliferous in so far as they have been examined, and where they outcrop they stand up as hills above the adjacent sands.

These interbedded limestones were apparently formed under the same conditions as those of the underlying series, because they contain in places layers with the peculiar flat pebble-like structures and scattered oölite grains. Certain beds have peculiar wavy structures which give to the rock an appearance somewhat like the fossil *Cryptozoon*, but it seems to be wholly due to a mechanical distortion by lateral compression of the thin beds making up the rock. Generally the contact between these interbedded limestones and the overlying sands is very obscure because of the rapid disintegration of the sandstone. In one case the transition was observed. In it the upper layer of limestone, about a foot thick, contained numerous flat pebbles and a few oölites scattered through it. This was succeeded by about two feet of very thin-bedded fine sandstone approaching shale in appearance, with numerous sun cracks or mud cracks distinctly preserved in certain layers. Then came the sand composed of extremely well-rounded sand grains.

The next overlying formation is a limestone, sometimes sandy and sometimes shaly, carrying a rather scant fauna of Lower

[1] Stose, *Folio 170, U.S. Geol. Surv.*

Ordovician age. In addition to the sandy and shaly layers and the normal limestones, several beds of oölitic rock are also present. In these the oölites are comparatively large in size and at many horizons have been replaced by silica giving rise to the siliceous oölites of this region which are represented in almost every geological collection.[1]

Beds of the peculiar thin pebble conglomerate already described under the Cambrian also occur here and, in fact, make up a half or more of the first few hundred feet of the Beekmantown limestone. These conglomerate layers vary somewhat in character. In every case examined the pebbles consist of extremely fine-grained calcareous material and, except on weathered surfaces, the conglomerate character cannot as a rule be easily recognized. On a fractured surface the interior of the pebble-like structure is almost identical in appearance with the surrounding matrix. On a weathered surface these structures show a different, generally lighter, color and are easily recognized. They are exceedingly variable in size and shape. In some beds they are round or oval and when viewed in the hand specimen have the characteristic appearance of water-worn pebbles. They are generally thinner in one direction and in thin section often show a peculiar concentric banding following parallel to the broader sides. Occasionally a pebble can be found with a fossil shell inclosed. In the majority of the beds the pebbles are broad and flat, ranging up to three or four inches in diameter and generally less than half an inch thick. They are found in all positions in the beds, some lying flat parallel to the bedding planes and some even standing on edge. Under certain conditions these broad flat pebbles have been replaced either in part or completely by silica in the form of chert, while the surrounding matrix remains calcareous. When only partially replaced, the replacing silica forms shell-like layers around the exterior of the structure, while the central part remains calcareous and unchanged.

[1] For published descriptions of these see V. Ziegler, *Am. Jour. Sci.*, 4th ser., XXXIV (1912), 113–27; E. S. Moore, *Jour. Geol.*, XX (1912), 259–69; G. R. Wieland, *Am. Jour. Sci.*, IV (1897), 262–64; J. S. Diller, *Bull. U.S.G.S. No. 150* (1898), pp. 95–97; E. O. Hovey, *Bull. Geol. Soc. Am.*, V (1893) 627–29; E. H. Barbour and J. Torrey, *Am. Jour. Sci.*, XL (1890), 246–49.

This series of strata, ranging from the Upper Cambrian well into the Ordovician, represents a peculiar combination of oölites, rounded sand grains, and unusual conglomerate-like beds which requires more than ordinary conditions of sedimentation to explain. After detailed study both in the field and in the laboratory, it seems to the author that these structures can be best explained individually, and as a combination, by the following series of events.

Toward the close of Cambrian time an epicontinental sea covered this region. The adjacent land area was in a state of peneplanation, thus furnishing very little clastic sediment but probably still contributing considerable quantities of calcium carbonate in solution. This lime carbonate was removed from the sea water and deposited as limestone by the activities of marine organisms. Marine animals, trilobites, brachiopods, and probably many other less highly organized types like the sponges aided in this work, but the greater part of the separation and secretion of the lime was brought about by marine algae which gave rise to the oölites and peculiar pebble-like structures. Then the region was somewhat elevated and sand-dune conditions prevailed. These marine limestones were covered over by a thick blanket of wind-blown sand. This material was worked over by the wind so long and so thoroughly that even the minute grains were rounded into almost perfect spheres. This sand resembles, but is even more rounded than, the beach and dune sand along the Florida coast today, which has gradually been carried southward by the wind and water and rounded during its journey. The region was not very far above sea-level and at least twice during the accumulation of these sands it was submerged and thin beds of limestone similar to those of the preceding period were formed. After this complete series of sandstones and limestones had accumulated, the whole region was finally submerged and the continuous marine sedimentation of early Beekmantown time was inaugurated. However, marine algae were still the important agents in producing the limestone, because, as already noted, oölitic limestone and siliceous oölite occur at numerous horizons and a large percentage of the lower beds is composed of the peculiar pebble-like conglomerate secreted by the algae.

These structures are of sufficient importance to require further explanation and it will be advisable to consider them one at a time, taking the conglomerates first, the oölites next, and the interbedded sands last.

ORIGIN OF THE CONGLOMERATE-LIKE STRUCTURES

Conglomerates from widely separated regions, similar to those here mentioned, have previously been described by other authors.

In 1906 a similar if not identical conglomerate was described by Seeley from Division D of the Beekmantown of the Champlain Valley, under the name of the Wing conglomerate.[1] He quotes Wing's original description of this conglomerate as follows: "A conglomerate made from flat and rounded pebbles from the quartzite below, the flat ones one or two inches across, the rounded ones from coarse shot to large bullets, the paste a limestone." After questioning as to the origin of these pebbles, Seeley remarks that the associated deposits seem to have been laid down in quiet waters and that the flattened pebbles, as described by Wing, stand on edge and at all angles. He was unable to imagine how in either swift or slow water these pebbles could be laid down as they are if they were of clastic origin. As a result of his studies he concluded that they were organic and he described the pebbles as *Wingia*, a new genus of Beekmantown sponges.

In 1909 Stose described conglomerates identical with those now under discussion from the same geological horizons near the southern boundary of Pennsylvania.[2] He offers the following explanation of their origin:

> At the beginning of the Conococheague an uplift occurred that raised a part of the sea bottom into land. The freshly deposited sediment was broken up and its fragments formed conglomerates, which also contain numerous rounded quartz grains. Other thin layers of limestone were broken up by the waves into "shingle" or flat fragments that were shuffled about on the beaches and formed "edgewise" conglomerates.

A very careful study of these conglomerates, both in the laboratory and in the field, with attention directed not only to the larger

[1] H. M. Seely, *Report of the Vt. State Geol.* (1906), pp. 174–78.

[2] G. W. Stose, *op. cit.*

structures of the conglomerate bed, but also to the minute microscopic structure of the individual pebbles, has brought out some interesting features not hitherto noted in the descriptions. It has already been stated that these peculiar conglomerate pebbles have a wide range in size and shape and that they occur associated with oölite grains. Although the pebbles are broad and flat, the edges and corners are always rounded. Thin sections cut from these pebbles show a peculiar banding in the broad flat types and a concentric structure in the smaller rounded specimens (Figs. 1, 2). The pebbles are frequently partially or completely replaced by silica in the form of chert. In such cases the matrix weathers away and leaves the replaced pebbles like chert concretions. If the replacement is incomplete and a joint plane passes through the pebble, the central unreplaced part also weathers out, leaving the chert nodule hollow.

Fig. 1.—Cross-section of a broad flat pebble as it appears on a weathered surface. The weathering brings out the arrangement of the laminae. Natural size.

As an outcome of these studies it has been concluded that these structures are organic, resulting from the activities of calcareous algae. This conclusion differs from Seeley's in assigning the origin to algae instead of sponges. Seeley was undoubtedly led to assign these structures to the sponges because of the frequency with which he found them containing silica. He describes *Wingia* as "a calcareous fossil sponge, with or without siliceous spicules . . . . the essential structure a collection of pillae or tufted balls, these mostly 0.25 mm. in diameter, massed without definite arrangement or rarely more loosely distributed through the containing calcite." These siliceous structures are no doubt replacements of the original calcite similar to those found both in the pebbles and in the oölites of the Pennsylvania region.

The importance of the lime-secreting algae seems to have been generally overlooked in explaining the origin of early Paleozoic limestones. Even in the building-up of modern calcareous deposits

these forms have been given scant credit. A recent contribution on this subject[1] by Howe has indicated how important these organisms really are in building up the reefs of today. The lack of recognition of these forms as important reef-builders is no doubt due to two facts. In the first place, the skeletons of these calcareous algae either have been assigned to true corals and therefore credited to the animal kingdom, or, on the other hand, they have perhaps been considered by some, direct chemical precipitates rather than organic structures. In the second place, these calcareous algal skeletons lose their organic character with great rapidity. Walther has shown by his studies on the *Lithothamnion* bank in the Bay of Naples that by the action of the percolating water the *Lithothamnion* structure is gradually obliterated and the calcareous mass becomes a structureless limestone. In studying Nullipore chalk from the Tertiary and from the Lias, Walther found that in many parts there occurred well-preserved specimens but in other parts a gradual obliteration is observed of all plant structures until the rock becomes entirely structureless. If this be true for a form like *Lithothamnion* which is known to secrete a calcareous skeleton whose mineral composition is calcite, it is not surprising that all trace of organic structure is lost in other types which, like *Halimeda*, secrete their skeleton in the mineral form of aragonite.[2]

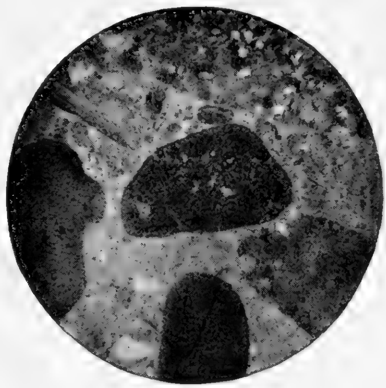

Fig. 2.—Thin section of small pebbles showing concentric structure. Enlarged.

It is freely admitted that in these pebble-like structures from the Cambrian and Ordovician limestones no organic structure has been found sufficiently well preserved to prove conclusively that they are of algal origin, but their similarity to such structures now forming is very suggestive. In this connection it is worth

[1] M. A. Howe, "The Building of 'Coral' Reefs," *Science*, May 31, 1912.

[2] W. Meigan, *Centralblatt für Min., Geol., und Pal.* (1901), pp. 577, 578.

while to compare the following quotations concerning modern occurrences.

> There is also a small vegetable group, that furnishes a considerable quota toward the composition of the characteristic coral-rock. It is that of the peculiar seaweeds or lower algae known as Corallines or Nullipores. They are distinguished by the incrustment of their tissues with carbonate of lime, to such density that their vegetable nature is completely disguised; and, excepting for the absence of the characteristic pores, they might in many instances be mistaken for the coralla of the hydroid coral Millepora. . . . . In the deeper rock pools, and on the sea bottom generally, in the neighborhood of the reefs, another generic form, Halimeda, belonging to the same nullipore tribe, is locally abundant. This type forms erect, branching tufts, often several inches in length, of which the branchlets are composed of flattened, irregularly polygonal, or more or less fan-shaped, calcareous disks, strung together, as it were, in a moniliform or chainlike order. While growing, this nullipore is a brilliant grass-green, but it bleaches, when dead, to a pure white. The bleached discoidal segments of its disintegrated fronds often occur in great abundance among the mixed calcareous components of reef-rocks and coral sand.[1]

In describing the reefs of the Bahamas Agassiz says:

> Nullipores are most abundant on the summit of the reef, growing upon the smaller fragments of broken corals, which they also often cement together, when they are forced inward into the deeper part of the lagoon, where the cemented masses frequently form heads of considerable size. Longitudinal and cross-sections of the lagoon show that its bottom is uniformly covered with coarse sand and broken shell material, or fine sand, according to the distance from the action of the breakers. Upon this looser material algae and corallines thrive and grow abundantly, generally in large patches.[2]
>
> Immense masses of nullipores and corallines grow on the shallowest flats, on the tops of the branches of madrepores which have died from exposure to the air, either because they have grown up to the surface and so have become exposed by extreme low tides, or because strong winds have blown the water from the flats.[3]

Not only are the Nullipores very abundant in many of the modern coral reefs but they also seem to be able to grow with great rapidity and they can live under all conditions—in deep water beyond the range of corals; in shallow water where they are

[1] W. Saville Kent, *The Great Barrier Reef of Australia*, (1893), pp. 140–41.

[2] Agassiz, *Bahamas*, p. 104; *Bull. Mus. Comp. Zoöl.*, XXIV (1894).

[3] Agassiz, *Three Cruises of the "Blake,"* I, 82.

uncovered for a part of the time each day; in the tropics where the water is warm; and in the cold waters north of the polar circles.

The remarks of Saville Kent concerning the disklike fragments of *Halimeda* mingled with the sands of the great barrier reef are very suggestive of the disklike structures here described. The range in size of these disks is very much greater than that found in the modern *Halimeda* but it is quite possible that a giant *Halimeda*-like form existed in these early paleozoic seas and gave rise to the structures here described.

One feature of the conglomerate beds yet awaits explanation; namely, the peculiar position frequently occupied by the broad flat pebbles, either on edge or at any angle to the bedding planes. Several explanations of this feature have previously been offered. As noted above, Seeley believed these pebbles were formed by sponges growing in place. Stose thought that they were formed by thin limestone layers breaking into small flat plates or shingle and tossed about on a tide-swept flat. When the tide came in, these flat fragments were washed together in all positions and held by a soft paste which surrounded them. This explanation seemed impossible to the author for two reasons: first, it would not account for the wide variations in the thickness of the conglomerate beds, which varies from a few inches to several feet, each bed being a definite unit and separated from those adjacent by parallel bedding planes; and secondly, it seemed impossible to conceive of the physical conditions which could roll these flat pebbles around until their edges and corners were rounded and then leave them indiscriminately mixed with a soft matrix, some lying flat, some on edge, and others at all possible angles between these two.

The true explanation of the origin of these conglomerates became apparent when a locality was visited along the railroad cut of the Lewisburg and Tyrone division, Pennsylvania R. R., beside the Logan Branch of Spring Creek, at a point opposite the Nittany Furnace in Bellefonte. At this point several hundred feet of limestone beds are exposed in a steeply dipping series along the railroad cut. The excavation in this cut has exposed the beds in vertical section and the arrangement of the broad flat pebbles becomes at once apparent. This arrangement is clearly shown in

the accompanying diagram and photograph (Figs. 3, 4). Here the pebbles are seen to be arranged in unsymmetrical wavelike or ripple-like structures which traverse the limestone. In this cut the beds are exposed at right angles to these wavelike structures and the arrangement is brought out with almost diagrammatic clearness. Each series of waves is confined to its own particular stratum of the limestone. When the wavelike layer of flattened pebbles arches up to form an unsymmetrical anticline the fine-

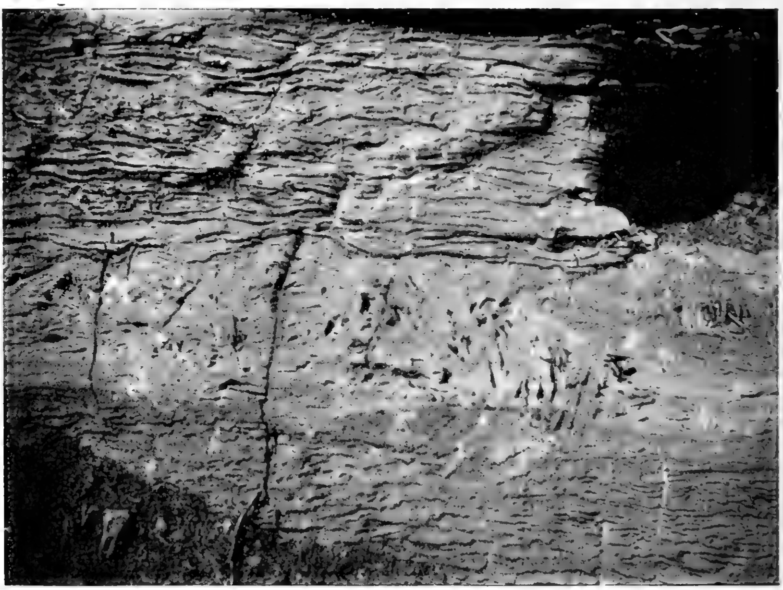

FIG. 3.—Photograph of a thin conglomerate layer in place, near Bellefonte, Pa.

grained material fills the space beneath the anticline down to the prominent bedding plane below. The space between the upper surface of this pebble layer and the next overlying prominent bedding plane is also filled by fine-grained material, which thickens over the synclines and thins out over the anticlines.

The explanation offered for these structures is this: The sediments composed of fine-grained calcareous mud resulting from the grinding-up of calcareous organic structures by wave action and broad flat pebble-like bodies which were the skeletons of cal-

careous algae accumulated on the gently sloping bottom of the sea. When in their original position these pebbles were all flat and parallel to the bottom; in other words they lay parallel to the bedding planes. At periodic intervals these beds of calcareous mud and intermingled pebbles slumped or slid along the bottom under the influence of gravity. At the time of the slump or slide the matrix around the pebbles consisted of incoherent lime mud or paste. As it moved it developed unsymmetrical waves or ripples

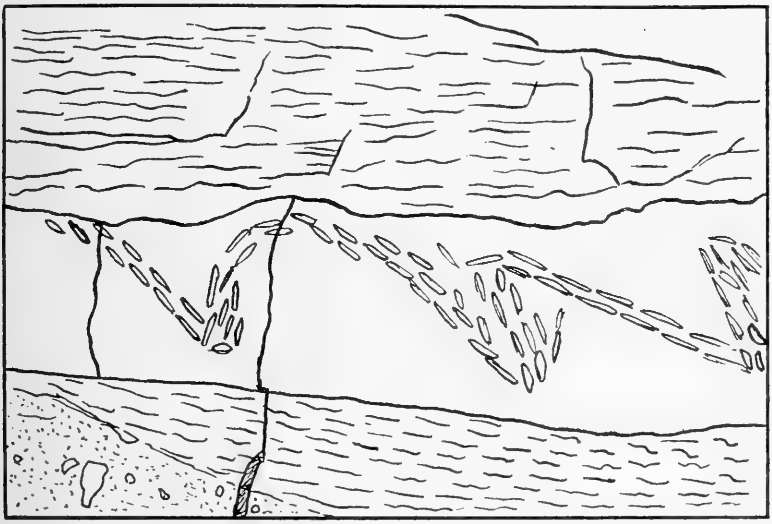

FIG. 4.—Diagram illustrating the arrangement of the pebbles shown in Fig. 3. The conglomerate bed is 6 inches thick and the distance from crest to crest of the wavelike structures is $9\frac{1}{2}$ inches.

in its mass, just as a thin sheet of water develops ripples as it flows down a smooth, gently sloping surface. The whole layer of sediment when it finally came to rest—and the whole distance moved may have been only a few inches or possibly a few feet—settled into a uniform layer once more, but the inclosed pebble-like structures had been moved from their original horizontal position, and occurred at all angles with the original bedding planes. In these new positions, surrounded by the matrix of lime mud, they were in perfect equilibrium and there they remained until the lime mud became transformed into limestone. And there we find them today when

properly exposed in cross-section, still indicating the wavelike flowing motion which brought them into their present position.[1]

ORIGIN OF THE OÖLITES

Oölites are widely distributed in the rocks of this country and Europe and are found at many horizons from the Cambrian (or even pre-Cambrian)[2] to the present. They are known to be accumulating today at numerous places among which may be mentioned certain coral reefs in the open sea, as, for example, those around Bermuda and the Bahamas, in Salt Lake, Utah, and in certain petrifying springs like those at Carlsbad.

The oölites of the central Pennsylvania region are somewhat variable according to the horizon at which they occur. In the Upper Cambrian limestones they are apparently all calcareous, either spherical or oval in shape, composed of concentric layers of material generally showing a radial fibrous structure. Between crossed nicols some of the spherules show a characteristic dark cross, while others have been almost completely transformed into a single calcite crystal with twin lamellae distinctly developed. No nuclei of foreign material were observed; the fibrous concentric structure continued to the center, or the calcite crystal occupied this central position with only the marginal fibrous part remaining. Associated with these spherical forms were numerous oval and rodlike structures having an internal make-up similar to that of the oölites. The spherical oölites range in diameter from 0.28 mm. to 0.73 mm. The oval and rodlike grains also show considerable variation in size, as these measurements will show: large oval oölite grain, long diameter 1.02 mm., short diameter 0.57 mm.; small oval grain, long diameter 0.86 mm., short diameter 0.28 mm.; long rodlike grain, long diameter 2.04 mm., short diameter 0.28 mm.

The siliceous oölites and the associated calcareous oölites from the Ordovician beds are sometimes larger in size. Several measure-

[1] I am indebted to Professor A. W. Grabau and Dr. F. F. Hahn of Columbia University, who first brought this explanation to my attention. Dr. Hahn has made a special study of such motion in stratified deposits. He informs me that in recent sediments in the Zuider Zee such a slumping or flowing of the sediments has been observed where the slope of the bottom did not exceed four degrees.

[2] See Geikie, *Text-Book of Geology*, p. 192, footnote.

ments of the spherical grains from that locality where they seem to be largest show that the range for the diameters is between 1.00 mm. and 1.33 mm. Many of the grains are partially or completely replaced by silica and a rounded sand grain frequently forms the nucleus around which these oölites have formed. In the course of this replacement the central nuclear sand grain is sometimes secondarily enlarged, showing a zonal structure in optical

5

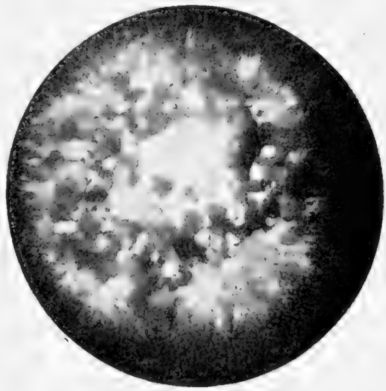

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FIG. 5.—Photomicrograph of siliceous oölite; ×22. The oölite on the left shows an oval sand grain as a nucleus, surrounded by cryptocrystalline quartz, with a narrow zone of minute quartz crystals radially arranged around the outer margin. The upper oölite shows the central nuclear quartz grain secondarily enlarged into a quartz crystal with part of the crystal faces developed. The lower oölite shows the central space occupied by an aggregate of minute quartz crystals. Nicols crossed.

FIG. 6.—The interior of the oölite of Fig. 5, ×130, showing the crystal outlines of the minute quartz grains which compose it. Nicols crossed.

continuity with the original grain and sometimes with more or less completely developed crystal faces. The outer zones of the spherules are generally replaced by cryptocrystalline quartz or chert. When no nucleus is present this chert may extend to the center or the center may be occupied by numerous distinctly crystallized quartz grains. Some of these show crystal faces as if the minute central cavity had been filled like a tiny geode. Another very interesting feature is the secondary enlargement of the spherules by one or more zones of crystalline quartz deposited in minute radial crystals arranged in zones around the original granule, with the long axes of the crystals arranged normal to the outer surface of the sphere (Figs. 5, 6).

Two theories have been advanced to explain the origin of these oölitic grains. Some hold that they are chemical precipitates and that the concentric oölitic structure is produced by successive layers of calcareous or siliceous deposit laid down on minute fragments of shells, sand grains, etc., in highly calcareous or siliceous waters. An alternative hypothesis, and one which seems more probable, is that cellular plants (algae) have extracted lime carbonate from the water, and have built this up into oölite grains with a concentric and fibrous radiated structure. All other types of oölites are then derived from these original calcareous grains by replacement. Such lowly organized plants can live even in hot waters, and oölite grains are now forming in springs like those at Carlsbad, due to the activity of algae.[1] In 1891 Rothpletz visited Salt Lake and made a detailed study of the oölitic sand now forming along the shore.[2] He found that oölites dredged up from the bottom, which had not been worked over by the waves, were covered with a deep bluish-green mass of algae among which he recognized *Gloeocapsa* and *Gloeotheca*. As a result of his studies he concludes:

> The oölites of the Great Salt Lake are, therefore, indubitably the product of lime-secreting fission-algae, and their formation is proceeding day by day. . . . . According to the present stage of my researches, I am inclined to believe that at least the majority of the marine calcareous oölites with regular zonal and radial structure are of plant origin, the product of microscopically small algae of very low rank, capable of secreting lime.

Another interesting suggestion, particularly when considered in connection with the foregoing discussion of the algal origin of the conglomerate-like beds, is that made by Seeley in which he called attention to the close resemblance of the internodal grains of Nullipores to grains of oölite as furnishing a further explanation of oölitic texture. These grains show a concentric structure as well as a radiated tubular structure, which would favor the recrystallization such as commonly occurs.[3]

In 1903 G. Linck published the results of his investigations

[1] Geikie, *Text-Book of Geology*, I, 191.

[2] *Botanisches Centralblatt*, Nr. 35 (1892). Translated in *Am. Geol.*, X (1892), 279–82.

[3] H. G. Seeley, *Brit. Assoc. Adv. Sci.*, *Bath* (1888), *Proc.*, pp. 674–75.

concerning the origin of oölites.[1] He proved that in every recent occurrence of oölite of which he was able to obtain samples, the oölite grains consist of the mineral aragonite, while in the older or fossil types they consist of calcite. He concludes that all oölites were originally formed as aragonite and later changed to the more stable mineral form calcite. But aragonite cannot form under any ordinary marine- or fresh-water conditions due to simple concentration of the solution of calcium bicarbonate. There are then two possible conditions under which the aragonite oölites might have accumulated. They might be the products of organic activity, for it is known that both animals and plants have the power to abstract calcium carbonate from the water and build it up into their skeletons in the form of aragonite. The skeletons of many of the coralline algae, for example, are formed in this way. The oölite grains might also be produced by direct chemical precipitation due to some special precipitating agent. By experimental research Linck found that, under ordinary conditions of temperature, the calcium carbonate would be precipitated from the calcium sulphate of sea water by the addition of sodium carbonate or ammonium carbonate. When so precipitated it assumed the mineral form aragonite. As a result of his investigations he concluded that although the solution of calcium carbonate (bicarbonate) in sea water was always below the saturation point, and therefore direct precipitation due to concentration could not take place, yet sodium carbonate or ammonium carbonate might arise, due to the decay of plant or animal tissues, and that these reagents would precipitate the calcium carbonate from the ordinary sea water, under either cold or warm climates, in the form of aragonite, and that in this way the oölite grains were formed.

This theory does not eliminate the organic factor in the production of oölite grains, but makes the organisms indirect agents which produce by their decay sodium or ammonium carbonate, the precipitating reagents, instead of directly building the oölite grains by their organic activity.

It would therefore seem that under either the organic or inorganic theory of origin we must postulate the presence of organisms

[1] *Neues Jahrbuch für Min., Geol., und Pal.*, Beilage-Band XVI (1903), 495–513.

to cause the formation of oölites. Now, since many of the oölite layers show no evidence of the presence of animal fossils, it would seem to be reasonable to assume that the organic agents were marine algae, either of the coralline type, somewhat similar to those which abound wherever oölites are known to be forming in the open sea today, or minute algae similar to those which are known to be active in the formation of oölites in Salt Lake or the hot springs of Carlsbad.[1]

In spite of recent publications to the contrary,[2] the author has in his possession material which will, he is convinced, when thoroughly worked up, prove that every occurrence of siliceous oölite in the Ordovician rocks of Pennsylvania is due to the direct replacement of an original calcareous oölite by silica. These siliceous oölites occur at many horizons and in many localities. They sometimes occupy widely extended layers, and sometimes occur as nodules in layers where the surrounding oölites are either calcareous or changed to dolomite. In every case when found in place, their field association and microscopic character is such that they could not have formed as direct chemical precipitates.

ORIGIN OF THE BARRENS SANDSTONE

As already noted, these sandstones are composed of fine, extremely well-rounded sand grains cemented by a calcareous or dolomitic cement which easily weathers out and gives rise to a thick mantle of residual sand. The sand grains seem to be uniformly rounded regardless of size. A thin section cut from the basal member of this series showed grains ranging from 0.17 mm. to 0.73 mm. in diameter (see Fig. 7). A sample of the residual sand from the middle of the series gave measurements from 0.13 mm. to 0.71 mm., and a similar sample from the upper beds showed diameters from 0.26 mm. to 0.86 mm.

As is well known, such fine sands could not have been rounded to such a degree in water. It seems, therefore, that the origin of these sands and sandstones must be assigned to the work of the

[1] The author has under way a further investigation of the origin of oölites, but the results are not yet available for publication.

[2] Ziegler, *Am. Jour. Sci.*, 4th ser., XXXIV (1912), 113–27.

wind. These sands are almost always pure white in color, differing from typical desert sands, which are generally some shade of red or brown, so that in all probability desert conditions did not prevail here. It was more likely a stretch of sand-dune country that lay along the low, flat Upper Cambrian shore. At that early day those types of plant life which check the development of sand dunes along our shores today did not exist and perhaps there was no other type of plant to take their place. As a result the wind had unhindered opportunity to get at and work over this sand. The climate need not have been very dry, because, as Shaler has shown, rain does not have an important retarding effect upon wind-blown sand.[1] Even heavy and long-continued rains falling upon dune sand rarely wet it for more than an inch below the surface. In a few hours after the rain is over, this thin film of water is evaporated from the surface and the wind is free again to move about the sand. The cross-bedding shown in the few localities where this sandstone outcrops is altogether consistent with this sand-dune theory of origin. When again the region became submerged, a little of the finer sand was carried out and dropped in the water. These grains then frequently served as the minute nuclei around which calcareous oölites formed, which were in many cases later replaced by silica and gave rise to the extensively developed siliceous oölites of the overlying beds.

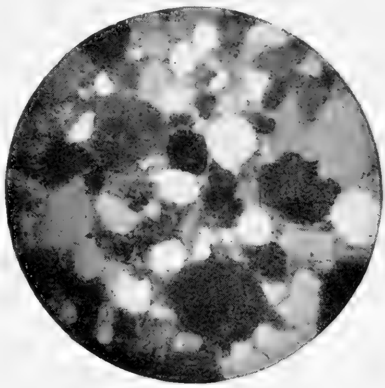

FIG. 7.—Photomicrograph of the Barrens sandstone. ×22. Nicols crossed.

This sand-dune theory of the origin of the sandstone beds does not require great changes in the conditions of sedimentation from the Upper Cambrian to the Lower Ordovician of this region, nor does it require long periods of time to produce the well-rounded character of the sand. Mackie has shown that sand carried by the wind for a very few miles will be more thoroughly rounded than

[1] N. S. Shaler, *Bull. Geol. Soc. Am.*, V, 207–12.

similar sands carried for many miles by water or subjected to long-continued churning by the waves.[1]

A slight elevation of the region, perhaps only a few score feet, would allow the sand dunes to migrate out over the Upper Cambrian limestones. No elevation of the adjacent land area is necessary to account for the transportation of the sand, because the wind is well able to transport sand grains of such small size for long distances if not interfered with by vegetation. Very slight depressions would account for the thin interbedded limestones, and a general though gentle submergence of the whole area would inaugurate Beekmantown time.

[1] Mackie, "On the Laws That Govern the Rounding of Particles of Sand," *Trans. Edinburgh Geol. Soc.*, VII, 298–311; see also pp. 148–72 (1897).

THE SECONDARY PRECIPITATION OF GOLD IN ORE BODIES

ALBERT D. BROKAW
University of Chicago

Secondary enrichment of ore deposits has been recognized as a subject of fundamental importance to the economic geologist, and in recent years has received considerable study, both in the field and in the laboratory. The chemical reactions involved are, in many cases, less complex and more readily susceptible to laboratory study than many of the other great problems of earth chemistry. The temperatures, pressures, and concentrations involved are well within the range easily obtainable in the laboratory; the reacting substances are less numerous, and their chemistry is better understood than is the case with the substances and reactions involved in petrogenesis.

In December, 1909, Emmons[1] published a paper calling attention to the relationship between placer deposits and manganiferous and manganese-free gold ores, suggesting manganese as a determining factor in the solution of gold. About the same time the writer began a series of experiments dealing with the solution of gold in secondary enrichment, the results of which were published in May 1910.[2] In October, 1910, Emmons published a somewhat comprehensive review of the chemical and geological data available, with special reference to the gold deposits of the United States.[3] Very little material bearing on the subject has appeared since that time, and at the suggestion of Dr. Emmons the writer undertook a series of experiments with the hope of clearing up some important points in connection with the chemistry of the precipitation of gold, and in particular, of establishing the peculiar set of conditions under which gold and manganese dioxide may be precipitated

[1] W. H. Emmons, *Min. and Sci. Press*, XCIX, 751–54, and 782–87 (1909).

[2] A. D. Brokaw, *Jour. Geol.*, XVIII, 321–26 (1910).

[3] W. H. Emmons, *Trans. Am. Inst. Min. Eng.*, XLII, 1–73 (1911).

simultaneously, since manganese dioxide has been considered favorable, if not essential, to the solution of gold in secondary enrichment.

The methods of precipitation here discussed are not necessarily limited to secondary enrichment. Gold from a primary deposit may be recrystallized; that is, may be dissolved and reprecipitated without appreciable transportation, and in this case no enrichment would be accomplished, though the chemistry of the precipitation might be essentially the same as that in which gold deposits are enriched. For this reason the writer does not hesitate to draw examples from deposits where the gold has been recrystallized by secondary processes even though the deposit is not thought to have undergone any appreciable enrichment.

The substances in an ore body, capable of precipitating gold from a solution in which it is held as a chloride, may be grouped as follows:

I. Native elements, copper, silver, mercury, tellurium.
II. Sulphides, tellurides, etc.
  a) Simple—most of the common sulphides.
  b) Complex—sulph-arsenides and antimonides.
III. Ferrous compounds.
  a) In solution derived from alteration of iron sulphides.
  b) Primary minerals, as siderite, iron bearing calcite, etc.
IV. Manganous compounds.
  a) In solution, derived from alteration of manganese minerals.
  b) Primary, rhodochrosite.
V. Other inorganic substances, sulphur dioxide.
VI. Organic compounds.

I. NATIVE ELEMENTS

The metals preceding gold in the table of electrolytic solution tension[1] are capable of displacing it from solutions of its salts. The reaction may be expressed ionically as follows:

$$Au^{+++}+3Me=Au+3Me^{+}$$

in which Me stands for one equivalent weight of the metal in question. Copper and silver are not uncommon in gold deposits and are capable of bringing about such precipitation. Doubtless

[1] See Smith, *General Inorganic Chemistry*, p. 670; Walker, *Introduction to Physical Chemistry*, or any textbook of physical chemistry.

native mercury, arsenic, and antimony can act in a similar way. There is, however, little geological evidence of such precipitation, though it is conceivable that electrum may sometimes be formed in this way. Ransome[1] mentions the association of wire gold with native silver in the Breckenridge district, and here the silver may have been the precipitating agent. The other metals having a higher electrolytic solution tension than gold and occurring free in nature are not common in gold deposits, and no record of their having caused precipitation of gold is found. Tellurium, usually classed as a non-metal, may interact with gold chloride in solution to precipitate gold, as shown by the following equation:[2]

$$3Te+4AuCl_3=4Au+3TeCl_4$$

This may account, in part, for the precipitation of gold in the oxidized portion of gold telluride deposits.

II. SULPHIDES, TELLURIDES, ETC.

a) *Simple sulphides.*—That sulphides are capable of precipitating gold has been known for many years. In 1866 Wilkinson[3] showed that metallic gold is precipitated by the sulphides of copper, iron, arsenic, lead, zinc, molybdenum and tungsten, and to this list Skey[4] added the sulphides of tin, bismuth, platinum and gold. These investigators showed that the precipitates obtained were metallic gold, not gold sulphide, though the latter would be the compound naturally expected by some such reaction as follows:

$$2AuCl_3+3ZnS=Au_2S_3+3ZnCl_2$$

It is of interest to consider the possible reasons for the precipitation of the metal instead of the sulphide.

Hydrogen sulphide, under ordinary conditions of temperature and pressure in the laboratory, reacts with gold salts in solution to form Au_2S_2,[5] a stable sulphide of extremely low solubility, as follows:

$$8AuCl_3+9H_2S+4H_2O=4Au_2S_2+24HCl+H_2SO_4$$

[1] F. L. Ransome, *U.S. Geol. Survey, Professional Paper No. 75*, p. 82.

[2] V. Lenher, *Jour. Am. Chem. Soc.*, XXIV, 355 (1902).

[3] *Trans. Roy. Soc., N.S.W.*, VIII, 11 (1866).

[4] *Chem. News*, XXIII, 232; see *J. B. u. d. Fortschritte d. Ch.*, 1871, p. 344.

[5] Gmelin-Kraut, V, P. II, p. 268.

Hydrogen sulphide may be formed by the interaction of acid mine waters on mineral sulphides, for example, on zinc blende, as follows:

$$H_2SO_4 + ZnS = H_2S + ZnSO_4$$

This reagent is doubtless an important precipitant for gold in such waters. Why then, does it throw down metallic gold in nature, instead of gold sulphide, as in the laboratory?

A number of factors may be mentioned as probable causes. Hydrogen sulphide is given off very slowly by most of the mineral sulphides except pyrrhotite and zinc blende, even in fairly strongly acid solutions. It has been shown that in the presence of auric chloride, gold sulphide is oxidized to metallic gold and sulphuric acid, with the further precipitation of gold from the solution,[1] probably according to the equation:

$$Au_2S_2 + 4AuCl_3 + 8H_2O = 6Au + 2H_2SO_4 + 12HCl$$

Since the hydrogen sulphide is very slowly evolved, it may be that the gold sulphide is momentarily formed and immediately oxidized by the adjacent gold chloride molecules, which have not yet been attacked by the hydrogen sulphide. The reaction was tested experimentally by placing in a dilute solution of gold chloride fragments of pyrrhotite and zinc blende, the mineral sulphides which give off hydrogen sulphide the most readily and are therefore the most favorable for the precipitation of gold sulphide. In the case of zinc blende the surface of the crystal was covered with shining flakes of gold after standing 24 days. No gold sulphide could be distinguished. In the case of pyrrhotite the action was more rapid and the gold was completely precipitated in 3 days, but here again no gold sulphide was detected. The pyrrhotite was covered with a dull yellowish-brown coat, which, under the microscope was shown to be made up of minute crystals of gold, partly imbedded in material resembling limonite.

A second possibility is that ferric salts may oxidize the gold sulphide in a similar fashion. With this in mind, a solution of gold chloride and ferric sulphate was treated with hydrogen sulphide solution until a dark precipitate began to form. A small amount

[1] Gmelin-Kraut, *loc. cit.*

of sulphuric acid was added to suppress the precipitation of ferrous sulphide. The solution and precipitate were allowed to stand over night, then filtered, and the precipitate was taken into solution with fuming nitric acid and a small amount of concentrated hydrochloric acid. If any sulphide were present it would be oxidized to sulphate under these conditions. The solution was diluted and filtered; barium chloride solution gave no precipitate, showing the absence of sulphates, and thus proving that no gold sulphide was present in the precipitate. It is conceivable under these conditions that the hydrogen sulphide may have reduced some of the ferric salt before the gold began to precipitate and that the ferrous salt precipitated the gold. If this had been the case the precipitate should have shown the presence of sulphur, according to the reaction:

$$Fe_2(SO_4)_3+H_2S=2FeSO_4+H_2SO_4+S$$

which takes place before the precipitation of ferrous sulphide begins. The action of the nitric acid in the above experiment would have oxidized such precipitated sulphur to sulphuric acid, and as the test showed the absence of sulphates it is evident that the above reaction did not take place, but that the hydrogen sulphide acted on the gold chloride. The gold sulphide, Au_2S_2, was probably formed first, then quickly oxidized to metallic gold and sulphuric acid by the ferric sulphate present.

A further experiment along the same line was made as follows: Gold sulphide was precipitated and placed in contact with ferric sulphate, free from ferrous salt. After two weeks the solution contained a noticeable amount of ferrous salt, showing that part of the ferric salt had been reduced by the gold sulphide, but the appearance of the precipitate had not changed appreciably. Fresh ferric salt solution was added with similar results, and after standing three months small particles of what appeared to be gold could be seen. They could not be separated from the gold sulphide however, and the evidence that they were particles of gold is far from conclusive.

From these experiments it seems likely that the presence of ferric salts tends to cause the precipitation of free gold rather than

gold sulphide, in the presence of hydrogen sulphide and sulphuric acid. Equations may be written as follows:

$$8AuCl_3+9H_2S+4H_2O=4Au_2S_2+24HCl+H_2SO_4$$
$$Au_2S_2+6Fe_2(SO_4)_3+8H_2O=2Au+12FeSO_4+8H_2SO_4$$

These reactions may help explain the fact that, so far as we know, gold sulphide does not occur in nature.

A number of natural tellurides, including all the commoner telluride ores, have been shown to react with gold chloride in a manner similar to that of free tellurium,[1] for example:

$$3Au_2Te+4AuCl_3=10Au+3TeCl_4$$

and as is the case with tellurium, this may help to account for the free gold in the oxidized portion of the ore body, such as the "rusty gold" or "flour gold" at Cripple Creek.

b) *Complex sulphides.*—From the fact that most of the simple sulphides precipitate gold from solution it is readily inferred that complex sulphides would be equally effective as precipitants. Polybasite was chosen for an experiment on this point. A small fragment of a good crystal of polybasite (Ag_9SbS_6) was placed in 5 c.c. of gold chloride solution containing 0.5 per cent gold. After 10 days the gold had been completely precipitated, forming a dull coat over the crystal, resembling that formed on pyrrhotite. Doubtless many of the complex sulphides would react in a similar manner, though geological observations bearing on such precipitations are lacking. Perhaps this is because the complex sulphide, after precipitating gold, has been more or less completely removed by oxidation.

III. FERROUS COMPOUNDS

a) *In solution.*—The fact that ferrous salts can precipitate gold from solutions of its salts has long been known. The reaction is ordinarily written:

$$3FeSO_4+AuCl_3=Au+Fe_2(SO_4)_3+FeCl_3\,,$$

or ionically,

$$3Fe^{++}+Au^{+++}=3Fe^{+++}+Au$$

This reaction was formerly used in metallurgical practice, but recently has been largely displaced by other methods. The

[1] V. Lenher, *op. cit.*

most abundant source of ferrous sulphate in mine waters is found in the iron sulphides, which, upon partial oxidation, give rise to ferrous sulphate and sulphuric acid. These are almost always present in the zone where the sulphides are undergoing oxidation, and, because of the downward movement of the waters, and the presence of reducing agents lower down, ferrous salts are likely to be abundant below this zone. In such an ore body gold cannot migrate far, since ferrous salts, even in small amounts, almost prohibit the transportation of gold in solution.[1] Ferrous salts in solution are more abundant in mine waters than is hydrogen sulphide, and are doubtless a more important factor in the secondary precipitation of gold.

McCaughey[2] showed the effect of ferrous salts on the solubility of gold in concentrated solutions of ferric salts, and doubtless an equilibrium condition exists between the concentrations of ferrous, ferric, and gold salts in solution, in contact with metallic gold. The equation may be written in the ionic form:

$$3Fe^{+++} + Au = 3Fe^{++} + Au^{+++}$$

whence the equilibrium equation:

$$\frac{[Fe^{++}]^3 \times [Au^{+++}]}{[Fe^{+++}]^3} = K$$

McCaughey's results were not sufficient to give the value of this constant, but more complete experiments would doubtless show such a relationship—indeed the form of curve obtained shows qualitatively that some such relationship exists.

If the condition of equilibrium were satisfied, fluorite may disturb it by going into solution and giving rise to the fluoride ion, which forms a little dissociated complex with the ferric ion,[3] practically removing it from the system and allowing the ferrous ion to cause precipitation. This case, though theoretically possible, is probably not of great importance in nature on account of the very low solubility of gold in ferric salts at concentrations obtaining in mine waters.

[1] McCaughey, *Jour. Am. Chem. Soc.*, XXXI, 1261 (1909). See also Emmons, *loc. cit.*

[2] *Loc. cit.*

[3] Stieglitz, *Qualitative Analysis*, Part I, 271 (New York, 1912).

b) *Primary iron minerals other than sulphides.*—Siderite is capable of precipitating gold from solution as follows:

$$AuCl_3+3FeCO_3+3H_2O=Au+3CO_2+FeCl_3+2Fe(OH)_3$$

Of this reaction we have geological evidence in the form of gold pseudomorphs after siderite, in which gold gives a sort of skeleton of the siderite replaced, since its volume is less than that of the siderite.

The specimen shown in Figs. 1, 2, and 3 is from the collection in Walker Museum, University of Chicago. The precipitation of gold by means of siderite was easily accomplished in the laboratory. A

FIG. 1.—Gold replacing iron carbonate. × 2

cleavage block of light-colored siderite was placed in 10 c.c. of 0.5 per cent gold solution, and after two weeks flakes of gold could be distinguished on the faces of the mineral. In another experiment sulphuric acid was added to the gold chloride solution. In this case the precipitation was more rapid, the siderite being nearly covered with shining flakes of gold after four days. After two weeks typical "wire gold" was noted, more or less coated with limonite. It is worthy of note that many occurrences of wire gold are found imbedded in a gangue of limonite. Ransome,[1] in describing specimens of gold from the Breckenridge district in

[1] F. L. Ransome, *U. S. Geol. Survey, Professional Paper No. 75*, pp. 81–82.

Colorado says, "The leaf gold is in exceedingly irregular masses, many of which consist of thin septa meeting at angles that strongly suggest deposition controlled in part by the cleavage planes of a rhombohedral carbonate of the calcite group. . . . . The [wire] gold does not occur in the clean, bright condition familiar in cabinet

FIG. 2.—Gold replacing iron carbonate. × 2

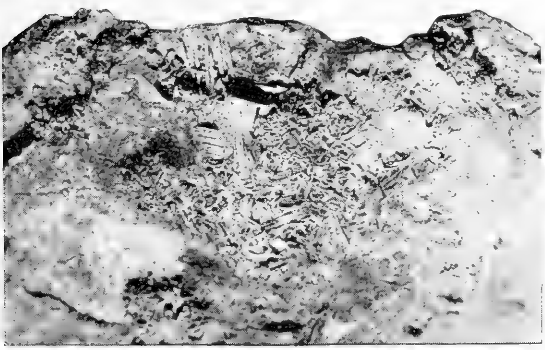

FIG. 3.—Gold replacing iron carbonate. × 2

specimens, but is imbedded in a reddish, earthy matrix, consisting largely of limonite, with oxides and carbonates of copper and various earthy impurities."

No doubt iron-bearing calcite can cause a similar precipitation, providing the iron is in the ferrous state of oxidation. Calcite is, of course, much more abundant than siderite in most gold

deposits. Analyses of calcite often show small amounts of ferrous carbonate, ranging in some cases up to 6 per cent. In sixteen analyses reported by Doelter[1] only three showed no ferrous iron, and the average for the sixteen was 1.33 per cent, reported as FeO.

Magnetite and olivine were selected as fairly simple ferrous compounds, and were allowed to stand in contact with a 0.5 per cent gold solution for 60 days. Neither one showed any precipitation of gold.

IV. MANGANOUS COMPOUNDS

a) *Manganous salts in solution.*—The fact that manganous salts, under certain conditions, can precipitate gold from solution and at the same time be oxidized to the insoluble manganese dioxide, seems to have escaped the attention of chemists. At least the writer has searched through chemical literature in vain for information on the subject. Wells[2] has called attention to the increased ease of oxidation of manganous salts in alkaline solutions, but the application to precipitation of gold has not been made.

The interesting occurrences of gold and manganese dioxide in a number of localities, notably in the San Juan,[3] Crede,[4] Park City[5] and Red Cliff[6] led to the suspicion that under the proper conditions manganous salts might act as the precipitating agent according to some such reaction as the following:

$$2AuCl_3+3MnSO_4+12H_2O=2Au+3MnO_2+6HCl+3H_2SO_4$$

Since this is the reverse of the reaction believed to be responsible for the solution of gold in the surface alteration of ore bodies, it is to be expected that it proceeds in this direction only under certain conditions, and the following series of experiments was undertaken with a view to ascertaining these conditions.

Gold chloride solutions of varying concentration were mixed with manganous sulphate solutions with concentrations ranging

[1] C. Doelter, *Handbuch der Mineral-Chemie*, I, 274–75. (Dresden, 1911.)

[2] Cited by W. H. Emmons, *Trans. Am. Inst. Min. Eng.*, XLII, 29 (1911).

[3] Ransome, *U.S. Geol. Survey, Bull. No. 182*, p. 101 (see also Emmons, *op. cit.*, 31).

[4] Emmons and Larsen, *U.S. Geol. Survey, Bull. No. 530.*

[5] *U.S. Geol. Survey, Professional Paper No. 77*, p. 103.

[6] S. F. Emmons, cited by W. H. Emmons, *op. cit.*

from normal up to saturation, but no precipitation occurred, even when the solutions were boiled for several minutes. All of these solutions gave acid reaction, due partly to the hydrolysis of the auric chloride:

$$AuCl_3 + 3H_2O = Au(OH)_3 + 3HCl$$

and partly to the addition product of auric chloride and water, H_2AuCl_3O, which ionizes as an acid[1] as follows:

$$H_2AuCl_3O = 2H^+ + AuCl_3O^=$$

It is well known that the efficacy of many reducing agents is increased by the alkalinity as is readily explained by the electrolytic theory of oxidation and reduction.[2] In accordance with this theory it was thought that neutralization of the acid solution might induce precipitation. N/50 potassium hydroxide was slowly added to 10 c.c. of a solution N/5 with respect to manganous salt and containing 75 mg. of gold as chloride. When about 6 c.c. had been added a brown precipitate began to form. The alkali was added until the solution was nearly neutral with respect to litmus, the precipitate was collected on a filter, and the manganese oxide was removed by digesting with a mixture of oxalic and sulphuric acids of known reducing strength. The residue was brought into a crucible, dried, and shown to be metallic Au.

In order to determine which oxide of manganese was formed in this reaction, the solution in the oxalic and sulphuric acid was divided into two equal parts. One of these was analyzed for manganese, and the other titrated with standard potassium permanganate solution to ascertain the loss of oxalic acid due to oxidation by the manganese oxide. The titration showed an oxidation of oxalic acid corresponding to one atom of oxygen for every molecule of MnO as determined in the analysis for manganese. The precipitate was clearly MnO_2, doubtless with water of hydration. In a check experiment the manganese oxide was taken into solution with a mixture of oxalic and sulphuric acids, equivalent to 45.28 c.c. N/10 alkali. After dissolving the precipitate the solution was equivalent to 32.26 c.c. N/10 alkali, having lost the equivalent

[1] Hittorf and Salkowsky, *Zeitschr. f. Phys. Ch.*, XXVIII, 546–55 (1899).

[2] See Stieglitz, *Qualitative Analysis*, Part I, 269 ff.

of 11.02 N/10 acid. The manganese in solution was then converted to manganese dioxide by a standard method[1] and redissolved in the standard mixture of oxalic and sulphuric acids. Essentially the same loss of acid was obtained (10.89 c.c.), proving the first precipitate to be manganese dioxide.

The equation for the precipitation may be written as follows:

$$2AuCl_3+3MnCl_2+12KOH=2Au+3MnO_2+6H_2O+12KCl,$$

or, ionically:

$$2Au^{+++}+3Mn^{++}=2Au^{+}+3Mn^{++++}$$

It is evident from the preceding experiments that the precipitation may start before all the acid is neutralized, depending on the concentration of gold and manganous salt in the solution. Consequently substances which can partially neutralize the acid ought to induce precipitation. To test this conclusion a mixture of gold and manganous chlorides[2] in solution was made up as before, and small crystals of calcite were added. After 3 days the crystals were entirely coated with a brown precipitate of manganese dioxide (hydrated) and particles of gold were distinctly visible on close inspection. The equation may be written:

$$2AuCl_3+3MnCl_2+6CaCO_3=2Au+3MnO_2+6CaCl_2+CO_2$$

b) *Manganese carbonate.*—In the similar way it was shown that rhodochrosite can cause the precipitation of gold. In this case the reaction doubtless involved an additional stage, as follows:

$$MnCO_3+2HCl=MnCl_2+CO_2+H_2O,$$

after which the reaction was analogous to the one obtained with calcite, with the substitution of $MnCO_3$ for $CaCO_3$. In both cases carbon dioxide was evolved in noticeable quantity. Doubtless manganiferous calcite can react similarly.

It must be admitted that the concentration of gold and manganous salts used in these experiments were greatly in excess of any reported mine waters, but higher concentrations were necessary in outlining the nature of the chemical reactions involved. It remains to be shown that similar reactions can take place in extremely dilute solutions. Accordingly a liter of N/500 manga-

[1] Clowes and Coleman, *Quantitative Analysis*, p. 259.

[2] $MnCl_2$ was used instead of $MnSO_4$ to avoid the precipitation of gypsum.

nous chloride solution was made up and 38 mg. of gold in the form of chloride was added. Very dilute potassium hydroxide solution was added in small amounts, with repeated shaking until the solution was almost neutral to litmus. Precipitation occurred at once. The precipitate was allowed to settle for 24 hours, then all but 100 c.c. was decanted by means of a slow siphon. The remaining solution was filtered and added to the decanted portion. A 50 c.c. portion was tested for gold by the phenyl hydrazine test[1] in a Nessler tube, with blank for comparison. As this showed no gold, 500 c.c. of the solution was concentrated to 100 c.c. and the test was repeated. This again gave negative results. The test used readily detects concentrations of less than one part per million, consequently the second test showed the gold remaining in the original solution to be less than two parts in ten million. Since the precipitation is so complete we are forced to the conclusion that these reactions can take place in solutions of extreme dilution—such solutions as would be formed in the leaching of gold from a manganiferous lode.

The fact that in certain cases mine waters actually show alkaline reaction is well established. Emmons[2] has shown that at Ducktown, Tenn., the waters show decreasing acidity with depth. This was for water in an abandoned shaft. For circulating waters the change is probably greater. It is doubtless due to interaction with the constituent minerals of the surrounding rocks.

The following list gives the more common gangue and rock-forming minerals showing alkaline reaction to litmus or phenolphthalein:[3]

[1] The phenyl hydrazine test mentioned has been described by Pozzi Escot, *Ann. de Ch. Anal.* (1907), XII, 90–91. It consists in adding to the solution to be tested, a few drops of formic acid, then a few drops of saturated phenyl hydrazine hydrochloride. The presence of gold is shown by a purple tint which may be used in the colormetric estimation of small amounts of gold. This method as tested by the writer gave strong tint in a 50 c.c. Nessler tube to solutions containing nine parts of gold in ten million of water. The advantage over the oxalic acid test is that the reaction is almost instantaneous and no heating is necessary.

[2] W. H. Emmons, *U.S. Geol. Survey Bull. No. 470*, p. 172.

[3] Kenngott, *Neues Jahrbuch* (1867), p. 302; F. Cornu, *Tschermak Mitteilung*, XXIV, 417–32, *a* XXV, 489.

Feldspars	Olivine	Calcite	Vesuvianite
Micas	Serpentine	Aragonite	Noselite
Pyroxenes	Talc	Dolomite	Sodalite
Nephelite	Tourmaline	Magnesite	Hauynite
Spodumene	Apatite	Siderite	

It seems certain that if gold in solution escapes precipitation by sulphides, ferrous compounds, etc., and if gold and manganese-bearing solutions remain in contact with ordinary wall rock or gangue minerals for sufficient length of time, the acidity will be sufficiently reduced to allow the simultaneous precipitation of gold and manganese dioxide in the ore body.

It must be noted in this connection that the amount of manganese dioxide mixed with the gold is usually far in excess of that required by the equation given on p. 262.

Ferric salts, the most abundant oxidizing agents in mine waters, do not oxidize manganous salts to manganese dioxide, even in alkaline solutions. This was shown experimentally by making a solution of manganous sulphate and ferric sulphate, and slowly neutralizing the solution. Iron hydroxide was precipitated at once, but the manganese remained in solution until the solution became alkaline, when it was precipitated as manganous hydroxide.

Wells[1] has suggested an explanation for the precipitation of manganese oxides below the zone of acid waters, by the presence of small amounts of permanganates in the mine waters, which react with manganous salts to form manganese dioxide as follows:

$$2KMnO_4+3MnSO_4+2H_2O=5MnO_2+K_2SO_4+2H_2SO_4$$

The acid liberated is taken up by alkalies in case of an alkaline solution. This reaction has been used in the volumetric determination of manganese and is doubtless important if permanganates are present. No data available show permanganates in mine waters, and this theory needs verification before it is accepted as correct. However, it seems to be the nearest approach to an explanation of the precipitation of the excess of manganese dioxide over the stoichiometric proportion to gold, or the precipitation of the substance in any conspicuous amounts. The order of pre-

[1] R. C. Wells, cited by Emmons, *Trans. Am. Inst. Min. Eng.*, XLII, 29 (1911).

cipitation would, in general, depend on the concentrations of permanganate, gold chloride, and manganous salt, and the acidity of the solution; a complex relationship which has not as yet been worked out.

V. OTHER INORGANIC SUBSTANCES

The number of inorganic substances capable of chemically precipitating gold, and occurring in ore deposits or mine waters, is doubtless rather large, but the more important ones only have been discussed.

Sulphur dioxide is used as a precipitant for gold, and either crystalline or colloidal gold may be formed by the action of this substance or sulphurous acid on solutions of gold chloride, the state of the gold depending upon conditions of temperature, concentration, etc.[1] Sulphur dioxide however is comparatively rare in mine waters, and probably may be neglected so far as precipitation of gold in an ore body is concerned. Similarly arsenious acid, and doubtless a great number of substance may be disregarded.

VI. ORGANIC COMPOUNDS

That a very great number of organic compounds can precipitate gold is very well known, and the idea that such precipitations occur in nature is by no means new. Rickard's experiments with the Rico shale[2] have been frequently referred to in the literature of ore deposits. Practically all organic compounds found in nature are reducing agents, and a very great number are strong enough to precipitate gold. Formic acid, oxalic acid, acetylene, glucose, and a host of others belong to the list.

Just what compounds are present in a carbonaceous shale, and just which of those present cause the precipitation, is at present impossible to say, but that many of them can cause precipitation seems unquestionable.

Amorphous carbon is capable of taking gold from gold chloride solution by absorption.[3] This seems to be a physical action

[1] See Gmelin-Kraut, *op. cit.*

[2] T. A. Rickard, *Trans. Am. Inst. Min. Eng.*, XXVI, 978 (1896).

[3] S. Brussow, *Zeitschr. Kolloid Chem. Ind.*, V, 137–38 (1909).

rather than a chemical, but amorphous carbon may be present in carbonaceous shales and supposably might cause such precipitation. Whether other amorphous substances are capable of causing such precipitation has not been rigorously investigated.

SUMMARY

If gold is in solution in waters circulating through an ore body many substances may cause precipitation of the gold. The ferrous compounds, derived from the partial oxidation of iron sulphides, are thought to be the most important, because they are formed comparatively readily from pyrite and other iron-bearing sulphides by the action of oxidizing waters,[1] they are very often, if not usually present in mine waters, and they are very effective precipitants for gold. The effect of the iron-bearing sulphides themselves cannot readily be separated from the action of ferrous salts, since in precipitating gold they may lead to the formation of ferrous sulphate, which, of course may cause farther precipitation of gold, if any is present. In most gold deposits sufficient pyrite, or other iron-bearing sulphide is present in the primary ore, to precipitate any gold that may be brought to the zone of sulphides. Less commonly siderite or iron-bearing calcite may be important. Siderite is attacked by acids more readily than pyrite, and consequently gives up ferrous salts more easily, and these, in solution, may cause the precipitation.

In comparatively rare cases, when the gold is in a solution containing manganous salts, contact with the country rock may neutralize the acids present and allow the manganous salt to reduce to gold. Rhodochrosite resembles siderite in its action except for the fact that no precipitation of gold can occur if the solutions are strongly acid, while in the case of siderite acidity does not inhibit the reduction of gold chloride to metallic gold.

The other reducing agents considered are thought to be of comparatively little importance, as they may be applied, to only a very few unusual deposits.

No attempt is made to explain the precipitation of gold from

[1] Buehler and Gottschalk, *Econ. Geol.*, V, 28–35 (1910), and VII, 15–34 (1912).

alkaline sulphide solutions, suggested by Lenher[1] as a possible means for the transportation of gold, as such solutions are not formed in the alteration of gold deposits. Their adequacy as a means for transportation and primary deposition of gold is beyond the scope of this paper.

In conclusion the writer wishes to express his thanks to Professor W. H. Emmons, who suggested this investigation, and to Professor Stieglitz, of the Department of Chemistry, for many helpful suggestions, on both theoretical considerations and practical experimental methods.

[1] Lenher, *Econ. Geol.*, VIII, 744–50 (1912).

ORIGINAL STREAMS; AND THEIR RÔLE IN GENERAL DESERT-LEVELING

CHARLES R. KEYES

Of all continental features rivers seem longest to persist through the geologic ages. The ocean's strand-line freely oscillates as relatively the land-surface rises or sinks, but watercourses flowing to the sea are little disturbed. They may be turned aside; but they usually quickly adjust themselves to the new conditions by merely lengthening or shortening their lower reaches. Some streams, we know, hold their original courses in spite of all orogenic obstacles thrown across their paths. Others conform closely to the local warpings of the earth's crust. Still others greatly extend their valleys by headward growth. But whether antecedent, consequent, or subsequent rivers, they are all directly descended from prior drainage-systems which stretch out indefinitely through geologic time and which even trace back their ancestry to the very beginnings of continents. Nowhere and at no time is there spontaneous generation of new streams or total extinguishment of old ones. Indeed, in a normally humid climate it could hardly be otherwise. In this respect, recorded observation and the necessary consequences of theory strictly accord.

In arid regions there appear to be certain phases of drainage which have no counterpart in moist lands. What little running water there is, is confined mainly to the slopes of the loftier desert ranges. In the mountainous deserts of southwestern United States, for instance, the rivers which once traversed the region and which once were supposed to have carved out the present great valleys are regarded as having long since lost all traces of their courses. With increasing aridity came general withering of streams. Hence only remnantal drainage now seemingly remains. The head-waters of the small intermittent streams are regarded as representing all that is left of former great rivers which have vanished under

the influences of a desiccating climate and as vast volumes of mountain waste deeply filled their valleys to form the present level intermont plains. As these arroyos are looked upon today they are the last vestiges of a once extensive consequent drainage.

In this connection one other point should be briefly noted. The general plains-surface of the region under consideration lies about a mile above sea-level; and above this surface rise another mile the rugged and isolated desert ranges. As in the case of the Great Basin region, it was long the custom to regard the mountain-ranges as tilted and upraised blocks, deeply dissected on all sides from which the resulting waste was carried directly out into the intermont basins. According to this view, the arid climate came over the region while it was already a mountainous country, much as it is today except more deeply sculptured, like the Rockies or the Appalachians are now.

There is another hypothesis applicable to the origin of these streams of the desert ranges; one which more closely accords with the conditions imposed by an arid climate. It is postulated that the mountains are products of differential erosion on an elevated plain composed of alternating hard and soft rock-belts.[1] The erosion of more than 5,000 feet is ascribed to deflation with little or no aid from stream-action.[2] That wind-scour under favorable conditions is amply competent to accomplish such work, that it is as potent an erosive agent as stream-corrasion and the washings of the rain in a moist climate is fully shown by the recent writings of many observers in various parts of the world, although in this country this subject has not as yet received the attention that it merits. Of these, mention may be made of the work of Obruchew[3] in central Siberia, of Walther[4] in North Africa, of La Touche[5] in the western Rajputana in India, of Berg[6] and Ivchenko[7] in the

[1] *Journal of Geology*, XVII (1909), 31.

[2] *Bull. Geol. Soc. America*, XXI (1910), 592.

[3] *Verh. Imp. min. Gesellsch. St. Petersburg*, (2), XXXIII (1895), 260.

[4] *Das Gesetz d. Wüstenbildung im Gegenwart u. Vorseit*, 1900.

[5] *Mem. Geol. Sur. India*, XXXV (1902), 10.

[6] *Pédologie pour 1902*, p. 37.

[7] *Ann. géol. min. Russie*, VII (1904), Pt. I, 43.

region about the Sea of Aral and in the Kirghiz steppes, of Passarge[1] and of Davis[2] in the South African veld, of Penck[3] in Palestine, of Hundhausen[4] in southern France, of Barron[5] in eastern Egypt, and of Blackwelder[6] in Wyoming.

The development of the drainage-lines in desert regions under conditions of general deflation is an aspect of arid erosion which has not, so far as I know, received the critical notice that it seems to deserve. Want of special attention to this single point has done more than any other one factor to mislead all who have traveled through the mountainous arid tracts of America, regarding the true ineffectiveness of the stream-erosion. Particularly deluding have been the impressions gained in such lands as those of western America. In many mountainous belts of that region there is, indeed, an apparent approach to normal stream-action as it is known in humid climates. Upon this really quite restricted and peculiarly modified effect of normal stream-work has been based the usual scheme of the arid cycle.

As is well known, the stratigraphy of the northern Mexican tableland, for example, is peculiar and remarkable in that the resistant rocks are mainly segregated in the lower part of the geologic column and the weak rocks in great thickness are confined to the upper part. In pre-Tertiary times chiefly the country was profoundly faulted, the average displacements being between 3,000 and 5,000 feet. As recently shown,[7] this region suffered planation and uplifting before the imposition of arid climate. If at the beginning of the cycle of aridity the surface were a plain, the present lofty ranges must have been differentially developed through the more rapid deflation of the broad belts of weak rock now constituting the areas of intermont plain.

As the mountains rear their forms more and more above the general plains-surface while the latter is being gradually lowered

[1] *Zeitsch. d. deutsch. geol. Gesellsch.*, LVI (1904), Protokol, 193.

[2] *Bull. Geol. Soc. America*, XVII (1906), 435.

[3] *American Jour. Sci.*, (4), XIX (1905), 167.

[4] *Globus*, CX (1906), 46.

[5] *Topog. of Sinai, West. Port.*, p. 17, 1907.

[6] *Journal of Geology*, XVII (1909), 429.

[7] *Proc. Iowa Acad. Sci.*, XIII (1908), 221.

through deflation, they finally become local rain-provokers of some small influence. During the period of arid youth the streams developed on the mountain slopes become slowly larger and larger, and longer and longer, until as the region is about to pass into its maturity, they attain their maximum size and efficiency. The mountains are now at their loftiest, their sides are steepest, the intermont plain encroaches deepest into them, the moisture gathered about them is greater in amount than at any time before or than will be afterward, the mountain watercourses reach their greatest extension, notwithstanding the facts that they carry relatively little water, are intermittent in character, and their lower reaches seldom pass beyond the foot of the ranges. Instead of being head-water remnants of extensive stream-systems which have long since withered away under the arid climate, as is a necessary consequence of the adapted normal-cycle hypothesis, they must be regarded as original streams coming into being as the differential effects of regional deflation become more and more pronounced. With the advancement of physiographic maturity these streams must begin to wither, and as senile relief approaches, they must, with few possible exceptions, undergo complete obliteration.

It is the custom to regard all water-action upon the desert ranges as normal stream-erosion in the process of dissecting recently upraised orographic blocks. This hypothesis seems to fall at once when it is considered that the major faulting of the mountain-blocks, is as already stated,[1] mainly very ancient, and not modern as has been so long assumed. Certain effects of general deflation have greatly aided in imparting to the mountain sides the infantile aspects of the stream-work. As recently suggested[2] the locus of maximum lateral deflation in the desert ranges is at their base, where plain sharply meets mountain without the intervention of foot-hills. The hard mountain-rock is encroached upon at the level of the general plains-surface as the sea gnaws away a line of its bordering cliffs, until, in many instances, the surface of the intermont plain extends into the mountain-blocks distances of several miles.

[1] *Bull. Geol. Soc. America*, XXI (1910), 543,

[2] *Science*, N.S., XXIX (1909), 753.

If the deflative hypothesis of regional desert lowering and leveling be accepted, we have in the desert ranges a stream-type hitherto unrecognized. The streams of this class have had no history previous to the youthful stage of the present geographic cycle, they have no prospect of relations with streams of a later cycle. Their birth, their span of life, their extinguishment are definitely circumscribed. They are the only existing streams we know of that do not have some sort of inherited relations with the waters of previous geographic cycles. They are the only streams the complete life histories of which may be distinctly traced. They are the only streams whose origin is clearly fixed in time and sharply limited in space.

THE NATURE OF THE LATER DEFORMATIONS IN CERTAIN RANGES OF THE GREAT BASIN

CHARLES LAURENCE BAKER

The department of paleontology of the University of California has lately made three expeditions into different regions of the southwestern part of the Great Basin with the main purpose of collecting Tertiary mammalian fossils. Incidentally a considerable body of new facts relative to the deformational and physiographic history of the later Cenozoic have been gathered, and a brief summary of some of the more important of these is here presented. No greater degree of accuracy than that implied by a rapid reconnaissance can be claimed for these statements. They apply to the following sections: the southern Sierra Nevada from the vicinity of Mono Lake southward to a point beyond Tehachapi Pass; the Black Mountain Range; the Calico Mountains of the central Mohave Desert; the El Paso Mountains, a short low range running *en echelon* with the southern Sierra Nevada southwest of Walker Pass; the northern White Mountain or Inyo Range on the boundary line between Nevada and California; the northern Silver Peak Range; the northern Pilot Range; the southern Gabbs Valley Range; the Cedar Mountain Range west and northwest of Tonopah, in central western Nevada; and the intervening basins.

The main tentative conclusion reached is that the conception of the extensive development of *normal* or *gravity* block faults *of great displacement* originally advanced by Russell and LeConte, and subsequently adopted by King, is fundamentally erroneous so far as this portion of the Basin Range province is concerned. In the opinion of the writer the Basin Ranges are really mountains of tangential compression. The evidence for this view is both structural and physiographic. The block faults, first described by Gilbert, can apparently be explained in considerable proportion quite as well as "upthrusts"—in the sense in which this

term was first used by Powell and C. A. White—as by the old conception of normal or gravity faults. Such of the faults as are really of the tensional type are probably those formed by the stretching of competent brittle rock along the flanks or summits of anticlines. There is so much of very competent rock in that region, and this is so commonly deformed by fracture rather than by flexure, that faults are very greatly developed and are often of great displacement.

The key to the problem is an old erosion surface, locally approaching the condition of a peneplain. This bevels the folded strata, and these contain a fairly abundant mammalian fauna of later Tertiary age. These folded and beveled later Tertiary beds have now been found in three widely separated localities of the southwestern Great Basin, namely in central western Nevada, in the central Mohave Desert, and in a region on the border line between the Mohave Desert proper and the rest of the Great Basin. The erosion surface cut out of these beds is in places warped into synclines, which form the valleys between many Basin Ranges, and into anticlines, which form the isolated ranges. In other places it is faulted, forming grabens in the cases of Death and Owens valleys and possibly elsewhere, and in other and more numerous cases tilted blocks bounded on one side by a fault scarp. The longitudinal profile of a block-faulted range, as determined by Louderback and the writer, is essentially that of the longer axis of an anticline. From a point of maximum movement the amount of displacement gradually dies out in either direction into monoclinal flexures and finally into undisturbed strata. Some of the Basin Ranges, as first pointed out by Spurr and Ball, do not owe their present forms in any sense to faulting but are merely structural upwarps or a series of anticlines more or less modified by erosion. Many of the intermontane basins are plainly seen to be true synclinal spoon-shaped basins. Gilbert's original suggestion that many of the Basin Ranges have their greater portions buried under their own débris is true only in a limited degree, for the original bed rock is found exposed at various places from the centers to the peripheries of some basins. In many of the basins the alluvium has not buried the post-Miocene

erosion surface, the formation of which antedated the latest deformation. The processes of desert erosion and deposition in an arid climate may mantle the rock surfaces of the ranges almost to their summits, and yet give only a very thin veneer above the bed rock, as mining operations at Tonopah and elsewhere have shown. In the immediate proximity of great fault scarps, the piedmont alluvial fans are, however, usually of great thickness, as on both sides of Owens and Death valleys.

The second uplift followed the axes of the first later Tertiary deformation but it seems to have been less intense, for the non-competent later Tertiary sediments, which were intensely folded in places and even overthrust during the first deformation, have been only gently warped during the second. This fact can be determined by the shape of the deformations in the peneplain produced during the first cycle of erosion. How much of the original folding of the non-competent later Tertiary beds has been due to a movement laterally over the basement of competent rocks which may have deformed mainly by fracture, is not known.

Zones of faulting along the bases of ranges have been examined by the writer in the Calico Mountains of the Mohave Desert in the Silver Peak Range in western Nevada and on the south base of the Sierra Nevada east of Tehachapi Pass. The fault planes in these localities approach the vertical and some even overhang. There is in the Silver Peak Range a zone of faulting rather than a single plane of faulting. The upthrown side forming the scarp is made up of the more competent and more erosion-resistant rocks, while the less competent strata on the downthrown side are closely compressed and overthrust contiguous to the faulting. In the Death Valley region, where faulting has probably taken place on as great a scale as anywhere in the Great Basin, closely folded Tertiary strata, referred to the Miocene by Spurr and Ball, bound the valley side of the Funeral Range fault. It is difficult to conceive how this folding and thrusting can have been caused by tensional stresses manifested in normal faults.

Gilbert's original conception of block-faulted mountains is incontestable. Gilbert never held, to the knowledge of the writer,

that all of the ranges of the Great Basin were of the block-faulted type, nor, as far as the writer knows, did he ever express the opinion in writing that the block-faults were all the results of tensional stresses.

On the contrary, Gilbert expressly states, on pp. 61 and 62 of Vol. III, U.S. Geographical Surveys West of the 100th Meridian, the following:

. . . . In the Appalachians corrugation has been produced commonly by folding, exceptionally by faulting; in the Basin Ranges, commonly by faulting, exceptionally by flexure. The regular alternation of curved synclinals and anticlinals is contrasted with rigid bodies of inclined strata, bounded by parallel faults. The former demand the assumption of great horizontal diminution of the space covered by the disturbed strata, and suggest lateral pressure as the immediate force concerned; the latter involve little horizontal diminution, and suggest the application of vertical pressure from below. . . . . It is, that in the case of the Appalachians the primary phenomena are superficial; and in that of the Basin Ranges they are deep-seated, the superficial being secondary; that such a force as has crowded together the strata of the Appalachians—whatever may have been its source—has acted in the Ranges on some portion of the earth's crust beneath the immediate surface; and the upper strata, by continually adapting themselves, under gravity, to the inequalities of the lower, have assumed the forms we see. Such a hypothesis, assigning to subterranean determination the position and direction of lines of uplift in the Range System, and leaving the character of the superficial phenomena to depend on the character and condition of the superficial materials, accords well with many of the observed facts, and especially with the persistence of ridges where structures are changed. It supposes that a ridge, created below, and slowly upheaving the superposed strata, would find them at one point coherent and flexible, and there produce an anticlinal; at another hard and rigid, and there uplift a fractured monoclinal; at a third, seamed and incoherent, and there produce a pseudo-anticlinal, like that of the Amargosa Range.

Spurr's general view that the present Basin Ranges owe their forms to folding modified by erosion, holds in part, but Spurr appears to have clearly recognized but one great deformation, the mid-Mesozoic, although he did mention the folding of Tertiary strata. He failed to recognize that the axes of later deformations often cut diagonally or at right angles across the axes of the mid-Mesozoic folding. The recognition of this fact was one of Louder-

back's main contributions; it was noted in several ranges by the geologists of the Fortieth Parallel Survey, and the writer has recently noted the same divergence of earlier and later axes of folding in two other Nevada ranges, the Pilot Range and the Cedar Mountain Range.

The recency of the movement to which the existing Basin Ranges owe their forms is such as to leave intact, in large measure, the superficial rocks of the lithosphere, even when these lie high in the zone that was affected by fracture during this deformation. We know this because there is still preserved much of the erosion surface developed previous to this deformation. It also happens that a large portion of this superficial rock is of a competent nature and, without any load, seems quite as likely, or more likely, to break than to fold. The Basin Ranges may very possibly have originated by tangential compression. Their present elevations and structures may be a joint product of the initial intensity of the deformative forces and of the relative resistance to deformation of the strata involved. This is a very elementary conception but is as far as the writer is willing to go on his present data.

The mid-Mesozoic deformation was apparently the most intense, the folds in the Death Valley region and in the Pilot Range being as close as those of the central Appalachians. The first later Tertiary deformation was probably on the whole less intense, although locally non-competent beds are closely crumpled and overthrust. The writer's studies have not been of such a detailed nature as clearly to separate the effects of these two movements on the older rocks. The most recent deformation is the least intense, at any rate as exhibited on the surface, but is the one which is responsible for the present orographic features of the Basin Ranges. What has happened in the zone of flow, or in the zone of combined fracture and flow, during this latest deformation, we have no means of knowing, since erosion has not yet laid bare these zones. But it is probable that in the southwestern portion of the Great Basin the competent brittle rocks at the surface or close to the surface have deformed somewhat differently from the dominantly sedimentary rocks of the Rocky Mountains, the Jura,

the California Coast Ranges, the central and northern Appalachians, the Alps, and the Himalayas, which are taken as classic types of tangentially compressed mountains.

There may be movements of mountain-making intensity in this province other than those outlined above; but these three have been found to be readily determinable. There are physiographic evidences of intermittency in the most recent uplift in central western Nevada.

EDITORIAL

CONTRIBUTIONS FROM ALLIED SCIENCES TO GEOLOGIC FUNDAMENTALS

Probably there never was a time in the history of our science when contributions from related lines of inquiry were more frequent or more vital than now. Certain it is that the related lines of inquiry were never before so numerous or so searching. Some of the results recently reached in geophysics, geodynamics, radioactivity, micro-seismology, geodesy, and other lines are singularly instructive. While it is scarcely possible for the working geologist, pressed to the limit by his own urgent inquiries, to keep a close watch on the procession of papers that pour forth from all the sciences that bear on his own, there is none the less need to follow as fast as may be in the wake of progress in related sciences.

Formal reviews and synoptical notices are indeed a great aid to this but as a rule these are prepared by those interested in the science to which the papers primarily relate, and for those so interested, and the bearings of these papers on geologic problems are rarely noted even if the author has dropped suggestions in this line. This need and this infelicity in the usual means of meeting it have given birth to the thought that it might be helpful if those geologists who have occasion to read in related sciences were to call the attention of their fellow-workers to points of special interest or value as they may find them, particularly if these points are such as seem likely to escape due appreciation. Of course if the new light comes with a dazzling flash, as did the Röntgen rays and the radioactive emanations it may be assumed that its own penetrating power will suffice, or if it comes in the disturbing fashion of seismic tremors these may be trusted to shake us up duly; but there are sources of light of a much gentler type that throw scarcely less luminosity on some of our dark problems. A note or a hint as these are met may serve busy fellow-workers a good turn. We venture at least to give the thought a trial.

If anyone feels that our science is losing something of its fearsome interest by the decadence of faith in the nether lake of fire, he may find some slight consolation by turning to the growing list of titles of this disturbing sort: "The Gravitational Instability of the Earth,"[1] "The Problem of Gravitational Instability,"[2] "On the Vibrations and Stability of a Gravitative Planet,"[3] and "On the Dilatational Stability of the Earth."[4] These themes open up quite a new line of inquiry relative to the central balancing of the earth. They imply the possibility that a symmetrical unstable centering of the earth's gravity is liable to pass into unsymmetrical stability. There is thus brought into consideration a possible diastrophism of a profound type. We take kindly to this for it seems a fresh line of support to the view that diastrophism may be as deep as the earth itself, a view that grows up naturally along with the thought of a growing earth with growing stresses at all stages. This view of gravitational instability may not be equally welcome to those who assign the earth a heart of gas, for if the central balance is ever unstable and becomes disturbed, the unbalanced stresses are favorable to the escape of the gas from its state of enormous compression and the stresses are withal well suited to aid in opening the way of escape.

If we feel forced to believe that the heart of the earth is less fluidal than we once thought, there is now the alternative of feeling quite sure that it is compressible. So long as we were taught that the atom was an ultimate thing, impenetrably hard and indivisibly coherent, there was ground to feel that when a planet became compressed in its central parts so that the atoms touched one another, compression could go no farther; but now that the approved picture of the atom is that of minute corpuscles revolving in orbits at prodigious velocities, some of them now and then flying the track and disclosing their small sizes and great speeds, the view of incompressibility loses all rational basis. Compressibility of

[1] A. E. H. Love, *Phil. Trans. Roy. Soc. London*, A, CCVII (1907), 171.

[2] A. E. H. Love, *Some Problems of Geodynamics*, University Press, Cambridge. England, 1911.

[3] J. H. Jeans, *Phil. Trans. Roy. Soc. London*, A, CCVII (1903), 157.

[4] Lord Rayleigh, *Proc. Roy. Soc. London*, A, LXXVII (1906).

the *atoms*, as well as reduction of interatomic space, is now definitely recognized as a possibility and even a probability by Richards[1] and others. The diastrophism of the atom is now to be a theme of inquiry, as well as the diastrophism of the earth.

Most of the old computations of geophysical application were based on assumed incompressibility, but mathematicians and geophysicists are already reworking their computations on the basis of compressibility. This finds expression in such recent titles as "General Theory of a Gravitative Compressible Planet," "Effect of Compressibility on Earth Tides," "Vibrations of a Gravitative Compressible Planet."[2]

It tallies well with the new ideas of compressibility that there should be coming to light new forms of familiar substances as these are forced to pass through changes of physical condition, particularly changes of pressure. Bridgman, in a group of notable papers,[3] recognizes *five solid forms of water*, and hints that there may be more. In this series of contributions there seems to us to be ground for the inference that molecular rearrangement may not improbably be a common rather than an exceptional property when conditions of pressure notably change. It is perhaps not too much to surmise that a *successon* of rearrangements of molecules may take place where there is a succession of marked changes of pressure, such, for instance, as would arise with increasing depth in the course of the earth's growth, assuming that it grew by solid accretions. Some few such rearrangements falling within the limits of the solid state are well known, but it now seems not unlikely that there may be a series of such rearrangements following the analogy of the five solid states of water treated by Bridgman.

[1] Theodore W. Richards, *Year Book No. 11*, Carnegie Inst. of Washington, 1912, p. 255.

[2] A. E. H. Love, *Some Problems of Geodynamics*, University Press, Cambridge, England, 1911.

[3] P. L. Bridgman, *Contributions from the Jefferson Physical Laboratory of Harvard University*, IX (1911), Nos. 4, 5, and 6; "The Measurement of Hydrostatic Pressures up to 20,000 Kilograms per Square Centimeter," *Proc. Am. Acad.*, XLVII, No. 11; "Mercury, Liquid and Solid, under Pressure," *Proc. Am. Acad.*, XLVII, No. 12; "The Collapse of Thick Cylinders under High Hydrostatic Pressure," *Phys. Review*, XXXIV, No. 1; "Water, in the Liquid and Five Solid Forms, under Pressure," *Proc. Am. Acad.*, XLVII, No. 13.

These contributions and the following one also strengthen the view that transitions of form take place by fractional action, portions passing to the fluid state and back again in succession while the larger portion at any one instant remains solid. It is of course well known that some geologists regard the deformations and movements of ice and of other crystalline rocks as a process of this kind, though more commonly assigned to viscous or plastic properties.

In the interest of sharper analytical discriminations, Johnson and Adams[1] have drawn clear lines of distinction between different *kinds* of pressure and their diverse effects. Their welcome paper clarifies a field over which fog has hung rather thickly. This clear demarkation of distinctions will no doubt help relieve "plasticity" of an overburden of service as the putative creature of hydrostatic pressure. It will then be free to come into proper service occasionally as *unbalanced* stress invokes it. Let us hope that the notion that *free and easy* movement goes with "pressure plasticity" may be honored with a place on the historic shelf, and that a place beside it may be reserved for its close cousin, the notion that "flow" of rocks under differential pressure carries the quality of facile fluency.

It is prudent to note, however, that new light is often only partial light, sometimes merely a dim dawning that may lead astray rather than make clear the true way. Some of the determinations of Tammann,[2] important as they are in themselves, were so interpreted at first as to seem to some geologists to lead back to the old view of fluidity wherever in the heart of the earth pressure is great, but the still more extended experiments of Bridgman with their acutely critical interpretations point to solidity and rigidity,[3] as do so many other lines of recent inquiry.

Most of these other lines are familiar, but the full significance of the determination of the body tide of the earth by Hecker[4]

[1] John Johnson and L. H. Adams, "On the Effect of High Pressures on the Physical and Chemical Behavior of Solids," *Am. Jour. Sci.*, XXXV, March, 1913.

[2] *Kristallisieren und Schmelzen*, Barth, Leipzig, 1903.

[3] *Op. cit.*, pp. 436, 437, 553–57.

[4] O. Hecker, "Beobachtungen an Horizontalpendelen," etc., *Veröff. d. Königl. preuss. geodät. Inst.*, 1907.

has not been adequately appreciated. Hecker found that the body tide rises directly under the tide-raising body. This implies that it is the tide of a rigid elastic body. Such a tide obviously has no effective influence in retarding the rotation of the earth by reason of lag; it is effective only in so far as energy is transferred by friction.

We have fallen much short of noting all the significant points in these valuable papers, but we venture to hope that the points cited may be helpful to some readers and may lead to an intimate acquaintance with the papers themselves. These seem to have a common trend, and to prophesy that we may in the near future tread a *terra firma* indeed, and may be permitted in time to build the history of the earth on a solid foundation in a literal as well as figurative sense.

T. C. C.

April 9, 1913

Reviews

Geological Expedition to Brazil and Chile, 1908–1909. By J. Woodworth. Bull. Mus. of Comparative Zoölogy, Harvard College, Vol. LVI. Shaler Memorial Series, No. 1. Pp. 137, figs. 37, pls. 37. Cambridge, Mass., 1912.

In commemoration of the long and distinguished services rendered to Harvard University by the late Dean Shaler, the alumni of that institution raised an endowment of more than thirty thousand dollars for the purpose of conducting appropriate investigations and publishing the results as a tribute to his memory. As the evidence of past glaciation was one of the lines of study which particularly commanded Professor Shaler's interest, and as he long ago anticipated the discovery of evidences of glaciers in the conglomeratic formations of the closing Paleozoic era, it seemed eminently fitting that a portion of the memorial fund be expended for further research on the Permian conglomerates of southern Brazil, the glacial origin of which was suggested by Dr. Orville A. Derby in 1888. This report is the result of an expedition organized for that purpose.

Following the itinerary and narrative of the expedition, there is given a brief outline of the geology of south Brazil based chiefly upon the publications of Derby and of Branner and the special report on the coal area by I. C. White. The formations which enter into the structure of southern Brazil may be grouped into the following terranes: (1) The belt of igneous and metamorphic rocks of the coast, including the Serra do Mar region, frequently classed as Pre-Cambrian and certainly Pre-Devonian. (2) The Devonian, including the sandstone cuesta of the Serra das Furnas and the overlying fossiliferous shales of Ponta Grossa in the state of Paraná. (3) The Permian series, including conglomerates and tillite beds as well as sandstones and shales, the latter coal-bearing in the south. (4) The Triassic sandstones and trap sheets, the latter making the escarpment known as the Serra Geral and its topographical equivalents elsewhere. (5) The Tertiary fresh-water deposits of the upland, and possibly along the coast. (6) The Recent deposits along the coastal borders, now slightly elevated.

The declared purpose of the expedition having been the investiga-

tion of the Permian glacial formations of southern Brazil, most attention was devoted to these interesting and significant deposits. Thick deposits of tillite were found quite extensively in the state of Paraná and in the adjacent portions of São Paulo and Santa Catharina. No glaciated rock floor, however, has yet been found in south Brazil, nor have the larger bowlders been found to bear striated surfaces, but the members of the expedition found ice-worn surfaces on pebbles and on fragments of rock ranging up to the size of a man's head. Distinctly striated pebbles had not been discovered previously in these deposits. While maintaining a position of reserve, Woodworth believes that the gorge of the Iguassu at the point where the railway crosses it at Serrinha Station affords evidence of two glacial epochs within the Permian.

The author refers to the hypothetical Gondwana-land and inquires whether it included Paraná-land. In particular he raises the question whether there was a land connection between South America and Africa in Permo-Carboniferous times. He follows Suess in thinking that the Atlantic Ocean basin may have had its origin in post-Triassic times! He says: "Certainly the assumption of an Atlantic trough in pre-Triassic times having anything like the present extent of the basin must be abandoned as being without sufficient geological evidence." He ends by saying: "We may conclude therefore that the geologist is free to converge the coasts of Africa and South America in Permian and earlier Carboniferous time as closely as any biological facts and geological evidences of land may demand for their explanation."

No doubt the great name Suess may warrant the taking of such convenient liberties with masses of continental dimensions, but to one who has toiled for a year or so on the ancient crustal wrinkles that face the South Atlantic it sounds like an excerpt from the Romance of Cataclysm.

As a possible aid to genetic hypotheses of low latitude glaciation the author cites at length from authorities to show the frequency and effectiveness of hailstorms in warm countries and elsewhere, and seems to lean toward an explanation of Permian glaciation along this line. He would perhaps have added to the value of his contribution if he had drawn a sharper line between hot-weather hailstorms that spring from violent columnar convection and which drop their ice product in the hot bed that gave them origin, on the one hand, and, on the other, the common case of frozen rain and sleet that form when the conditions are on the wavering line between freezing and not freezing. The former have the merit of giving an impressive demonstration of the nearness

of a glacial zone above us, while the latter are but details of the border ground of common ice precipitation.

The author confesses to uncertainty regarding the cause of the Permian and Pleistocene glaciations, but he takes only three sentences to do up "the recently elaborated hypothesis that glaciation may be brought about through the temporary reduction of the amount of carbon in the earth's atmosphere." He says this theory "leaves unexplained the shortly succeeding ice advances between whose dates no corresponding appreciable reduction in the carbon is registered by rock-making in the earth's crust." Something no doubt is to be allowed for infelicity in phrasing when one is giving so short a shrift to a theory, but the author seems to lack a close acquaintance with the view he rejects. There are different views in which carbon dioxide plays a part, but there is only one that has been "elaborated" in a geological sense. This view makes a radical distinction between a glacial period and its oscillations, as also between fundamental agencies that may bring on a glacial period and auxiliary agencies that can only impose oscillations on it. The glacial period in this view persists through the whole series of oscillations, and the fundamental agencies continue in effect and action throughout. The fundamental agency assigned by this hypothesis is world-wide diastrophism which acts on the atmosphere by the increased contact it gives, and leads to its depletion; it also acts physically and mechanically. The chief auxiliary agency assigned to the production of oscillations is the ocean which holds 90 per cent or more of all the free and semi-free carbon dioxide on the face of the globe. The ocean alternately absorbs and gives forth carbon dioxide as set forth in detail by the author of this view. It is misleading to say that this hypothesis "leaves unexplained" the glacial oscillations, for it not only offers an elaborate explanation but is without a rival in the explicitness with which it draws forth and lays emphasis on the character of these oscillations, particularly that singular combination of subequal ice advances with continually shortening time-intervals between them. The author was of course altogether at liberty to say that in his judgment the explanation is inadequate or incompetent, but readers will hardly commend his precision of statement when he tells them that it leaves unexplained the oscillations when in fact it offers the most explicit explanation yet put in print, except perhaps that of Croll on quite a different line.

In summarizing the geomorphology of south Brazil the author brings out clearly the two distinct topographic units, the tableland, or

planalto, and its steep coastal border which constitutes the Serra do Mar. The region was baseleveled in the late Mesozoic, and the summits of the Serra do Mar which rise above the plateau level were probably more resistant granitic bosses which had not been reduced to the base plain. Uplifts in Tertiary and subsequent times have contributed to the present elevation and to the existing status of erosion.

The bulletin closes with a note on the changes of level on the coast of southern Chile. Starting out with the intention of studying the nature of the Pleistocene and Recent uplifting of the Chilean coast, first described by Charles Darwin, Woodworth failed to find good evidence of any extensive rise of the coast in Quaternary times. A late Pliocene or early Pleistocene uplift of about sixty feet at Valdivia, a late Pleistocene uplift of forty-five feet at Concepçión, and a recent rise of lesser magnitude were indicated by these studies.

R. T. C.

"Formation of Coal Beds." II. By JOHN J. STEVENSON. *Proc. Am. Phil. Soc.*, Vol. L, No. 202, 1911.

The author of this article has prepared a careful survey of the literature bearing on the origin of coal beds. He has presented much data regarding the origin and character of transported organic matter and discussed the significance of floods and torrents as eroding and transporting agencies. There are three major divisions of the subject:

1. Rainfall barely disturbs the cover of litter in a forest and the latter is practically uninjured by the heaviest rainfall. Rainfall does not remove soil covered by vegetation unless this mantle is ruptured. Torrents produce but slight effects upon the rocks or vegetation over which they flow unless they carry considerable débris; trees of small and large diameter resist mountain torrents that are even loaded with coarse débris. Where the torrents come from regions having a good mantle of vegetable matter they are practically free from inorganic load.

2. Descriptions of peat deposits are included under this head and data from widely scattered regions are brought together showing the geographic and stratigraphic position of the beds, the botanical constitution, the appearance, thickness, and degree of consolidation. Peat consists of more or less altered plant material whose organic texture is recognizable and of an inclosing substance evidently derived from complete decomposition of the plant tissues. This is all more or less mixed with sedimentary sand, clay, or calcareous matter. Peat always contains a large amount of water. The fact is pointed out that peat does accumulate in the tropics

where topographic conditions are combined with the right humidity. Many peat beds are crowded with successive generations of trees growing on and in the peat and producing thick deposits.

3. Examinations of existing and buried peat beds has shown that they consist in part of trees and other vegetation *in situ* and of some drift material which can be recognized by its conspicuous lack of tender parts. There seems to be no difficulty in recognizing buried forests as such, and attention is called to the fact that in many great forested swamps broken and overturned stems are well preserved, while the stumps which have remained exposed to atmospheric action have decayed. The bedding and conformable relations of the various members of the coal series eliminate the probability of landslides as a great factor in coal formation.

E. A. Stephenson

Bulletin of the Seismological Society of America. Vol. I, No. 4, and Vol. II, No. 1.

This is devoted largely to seismology but is of great interest to the geologist as well as the seismologist. No. 4 contains a good biographical sketch of Major C. E. Dutton, an article on "Earthquake Epicentres," one on "Displaced Objects in Earthquake Motion," and an excellent contribution on some Canadian post-glacial faults, also many notes on recent earthquakes.

No. 1 of Vol. II contains biographical notes on Professor George Davidson and Professor John Milne, seismologist. Mr. Reid's article on the choice of a seismograph is interesting and valuable. The greater part of this number is devoted to a discussion of destructive earthquakes in China.

E. A. S.

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GLACIAL DEPOSITS OF THE CONTINENTAL TYPE IN ALASKA[1]

R. S. TARR AND LAWRENCE MARTIN

CONTENTS

[1] Based upon field work by the senior author in 1911, and by the junior author in 1910 and 1911. This paper was written after the lamented death of the senior author on March 21, 1912, and the junior author assumes full responsibility for all

INTRODUCTION

The glaciation of the interior of Alaska forms a striking contrast with that of the coast, where the glacial erosion forms predominate, the deposits being largely under water. The interior, between the coast ranges and the Endicott-Rocky Mountain system, where the National Geographic Society's parties made some studies in 1910 and 1911, has extensive glacial deposits of the continental type, similar to those of United States, and previously described in part by Dawson, McConnell, Russell, Hayes, Spurr, Schrader, Mendenhall, Brooks, and many others. From 1867, when Dall[1] first announced the absence of glaciation on the middle and lower Yukon, to 1906, when Brooks[2] summarized the knowledge of glaciation in Alaska, and continuing to the present time, there has been an increasing amount of specific information concerning the glaciation of the interior of Alaska. Most of this material has been gathered by the geologists of the Alaska Division of the U.S. Geological Survey.

In this paper it is proposed merely to call attention to the availability of this information and to emphasize the conditions in one of the large areas of glacial deposits of the continental type—the Upper Copper River valley—where we made our observations in 1910 and 1911. Here one type of deposit derived from the glacial drift, hitherto not described specifically from Alaska—wind-blown loess or eolian silt—occurs in considerable amount, and is still being deposited.

CONTINENTAL DEPOSITS IN ALASKA

The areas on the coast of Alaska where glacial deposits occur are relatively small—(*a*) 1,600 square miles east of Yakutat Bay, (*b*) 16,000 square miles in the Cook Inlet-Susitna valley region (perhaps to be considered an interior area), and (*c*) smaller areas.

possible errors of interpretation. Professor J. B. Woodworth has been good enough to read and criticize the manuscript.

Read before the Geological Society of America, December 28, 1911.

Published by permission of Henry Gannett, Chairman of the Research Committee of the National Geographic Society of Washington.

[1] *Amer. Journ. Sci.*, Second Series, Vol. XLV (1868), 99.

[2] *Prof. Paper 45, U.S. Geol. Survey* (1906), pp. 244–49.

The areas of continental glacial deposits in the interior are much larger and may be computed from Brooks's map (Fig. 1) as follows: at least (*a*) 15,000 square miles in the Copper River basin, (*b*)

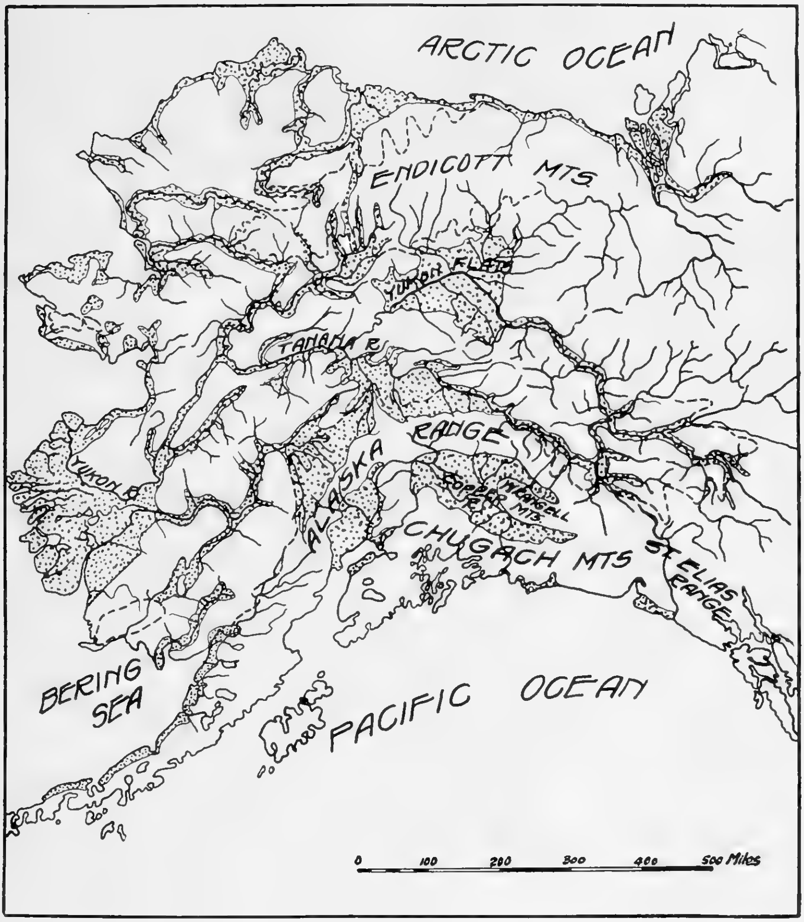


FIG. 1.—Map of Alaska showing areas of glacial deposits of the continental type (dotted areas). Boundaries of glaciation shown by dashed lines. (After A. H. Brooks.)

27,000 square miles in the Tanana and Kuskokwim valleys, (*c*) 17,000 square miles in the Yukon Flats, (*d*) several thousand square miles on the upper Yukon region in Canada, and smaller areas.

The Tanana–Kuskokwim valley area is clearly one of glacial outwash extending far outside the limit of glaciation, as the silt-laden streams from existing glaciers testify. Whether the Yukon Flats area is entirely glacial outwash is not absolutely clear. Russell thought it a flood-plain deposit and Spurr a lake bottom. The narrow strips of Pleistocene silts, sands, and gravels along the rivers, and the broad expanse of the Yukon–Kuskokwim delta have not been specifically considered in this paper, although distant existing glaciers are still supplying much of the sediment even to these regions.

GLACIAL DEPOSITS OF THE COPPER RIVER BASIN

The upper Copper River flows through an intermontane basin which it shares with the headwaters of the Susitna River. This basin is walled in by the Alaska Range and the Nutzotin, Talkeetna, Wrangell, and Chugach mountains. It is clear that the area of Pleistocene in the upper Copper River valley is wholly of glacial origin. The nature of this intermontane basin is such that practically none of the glacial débris escaped down the stream outlets.

Here the topography and the glacial material have been described in more or less detail by Hayes, Schrader, Mendenhall, Spencer, Moffit, Maddren, Capps, and others,[1] and here the junior author of this paper in 1910 and both of us in 1911 made the observations which form the basis of the present discussion.

Area covered by drift.—Throughout over 15,000 square miles (Fig. 1), an area at least equal to the portion of Illinois covered by drift deposits of the last glacial epoch, the basin of the upper Copper and Susitna rivers has glacial deposits which dominate the region.

[1] C. W. Hayes, *Nat. Geog. Mag.*, Vol. IV (1892), 135–36; W. C. Mendenhall, *20th Ann. Rept., U.S. Geol. Survey*, Part VII (1900), 282–84; F. C. Schrader, *ibid.*, pp. 384–86, 410–12; F. C. Schrader, and A. C. Spencer, House Doc. 546, 56th Cong., 2d sess. (1901), pp. 29–30, 58–61, 62–75; Oscar Rohn, *21st Ann. Rept., U.S. Geol. Survey*, Part II (1900), 408–9; W. C. Mendenhall and F. C. Schrader, *Prof. Paper 15, U.S. Geol. Survey* (1903); W. C. Mendenhall, *Prof. Paper 41, U.S. Geol. Survey* (1905), pp. 19–22, 62–74, 79, 88–90; F. H. Moffit and A. G. Maddren, *Bull. 374, U.S. Geol. Survey* (1909), pp. 37–42; S. R. Capps, *Bull. 417, U.S. Geol. Survey* (1910), pp. 36–42; S. R. Capps, *Jour. Geol.*, Vol. XVIII (1910), 38–39; F. H. Moffit and S. R. Capps, *Bull. 448, U.S. Geol. Survey* (1911), pp. 43–52; S. R. Capps, *Jour. Geol.*, Vol. XX (1912), 420–21, 428–30; F. H. Moffit, *Bull. 498, U.S. Geol. Survey* (1912), pp. 39–44, 51–53.

Except near the mountains, no rock outcrops are known. The topography is wholly glacial. The material is till, gravel, sand, silt, clay, and loess.

Thickness of deposits.—The observed thickness of the drift is 500–700 feet[1] in places, and may exceed 1,000 feet. This great thickness, in flat plains at a considerable distance from the mountains, forms a striking contrast with the drift of the region south of the Great Lakes, where it rarely exceeds 400 feet in thickness and averages 115 feet in Illinois, as determined by Leverett, and 40 to 250 feet in southeastern Wisconsin, as determined by Alden.

Plains topography.—The plains topography dominates the upper Copper River valley, the level of the country rising from 600–800 feet, at the southern edge near the lowest outlet of the basin across the Chugach Mountains, to 3,600 feet near the Alaska Range from which the northern portion of the glacial drift was derived, and 5,000 feet on the slopes of the Wrangell Mountains to the east. The broad area of monotonously even plains is shown along the route traversed in 1898 by Mendenhall, from Cook Inlet to the Alaska Range, a distance of over 100 miles, and our own route across this basin in 1911 from the head of the Copper River canyon at Chitina to the Delta Pass, 160 miles.

Streams have cut deeply (500–800 feet) into the outwash plain, opening out wide valleys, either because of recent uplifts, or, as we think much more probable, because of increased ability to erode because the retreating glaciers have retired into the mountains, are no longer excessively overloaded, and have replaced aggradation by degradation. Within the bordering mountain valleys this degradation results in the leaving of lateral terraces of thick bench gravels.

Dominance of outwash.—Outwash gravel, sand, and silt are the chief materials making up the surface of this plain, many of the beds being of alternate weakness and resistance. Lake deposits also make part of the flat topography.

Till of the normal sort.—There is also much till of the normal sort, covering large areas and 400–600 feet thick, but in much

[1] W. C. Mendenhall, *Prof. Paper 41, U.S. Geol. Survey* (1905), p. 63; F. H. Moffit and S. R. Capps, *Bull. 448, U.S. Geol. Survey* (1911), p. 49.

of the Copper River basin the till is buried beneath the outwash. Knobs and kettles, and lakes and swamps are abundant in the till areas. Kames and eskers are present, but thus far no one has found drumlins.

Alternation of beds.—The alternation of silt and gravel with bowlder clay suggests either a complexity of the period of deglaciation, or else that *pro*-glacial outwash gravels, laid down by glacial streams in front of the advancing ice sheet, are to be identified below the till beds, with *post*-glacial outwash, from the retreating ice, above. Sharply folded structures in the stratified clays and silts show the effects of this overriding. Weathering has not been recognized in the lower beds, so that interglacial epochs are not yet suggested by the Alaskan drift.

Volcanic complications.—Near the mountains the presence of lava flows, resting upon, and even intruded in, glacial deposits has been described by Schrader and Spencer,[1] and the complication of past and future ash showers upon the drift is suggested by volcanic ash in some parts of Alaska with thicknesses of a few inches to 75 or 100 feet in an area of many hundred square miles. Present eruptions of Mt. Wrangell, as in April, 1911, show that this process may occur in the future, leaving volcanic ash beds upon or inter-stratified with the till, outwash, and vegetation of the Copper River valley. In at least one locality 35 miles from the nearest active volcano, Mt. Wrangell, enormous masses of angular volcanic rock occur in blocks, buried in the outwash gravels and till beds, suggesting either volcanic showers of large bombs or material carried in glacial floods, as in Iceland. These volcanic fragments are abundantly exposed in 1910 and 1911 in cuts along the newly constructed railway, near Chitina. Other occurrences of the same sort are known, as much as 45 miles from Mt. Wrangell.

Lake deposits.—Large areas of very flat topography with clayey soil suggest former, local, glacial lakes, and some of the sections reveal over 300 feet of fine silt with a few scattered stones, perhaps dropped by floating icebergs. In some sections, measured by

[1] F. C. Schrader and A. C. Spencer, House Doc. 546, 56th Cong., 2d sess. (1901), p. 59 and Pl. XI, A, facing p. 54.

Mendenhall, no striated pebbles were found, but other clays with striated pebbles have been observed.

Sand dunes.—Overlying the outwash and till, in places, are dunes, and the thickness of the sand is over 20 feet in one case. The cross-bedded sand, in other localities beneath till, gravel, and clay suggests either older sand dunes or cross-bedded outwash, but whether in pro-glacial deposits or in recessional deposits of an earlier oscillation is uncertain. The dunes observed are at the very edges of bluffs and the wind-blown material was derived from the modern outwash plains. Dune sand has been described by Schrader and Spencer,[1] and by Mendenhall,[2] and the authors have observed the same phenomena near the junction of the Copper, Chitina, and Kotsina rivers.

Finer wind-blown material than the dune sand has not previously been observed to our knowledge, except by Schrader and Spencer in 1900. They noted[3] that "besides wind-blown deposits in the forms of dunes, the surface soil is frequently composed of fine sand, doubtless of similar origin, and careful investigation would probably show that eolian deposits are rather generally distributed over the Copper Basin."

THE LOESS OR EOLIAN SILT[4] OF THE COPPER RIVER BASIN

Localities.—The localities where we have observed loess soil or eolian silt are (*a*) at Chitina near the southern edge of the Copper River basin just north of the Chugach Mountains; (*b*) at a number of localities along the military trail between Chitina and the Delta River pass across the Alaska Range, scattered throughout a distance of over 160 miles; and (*c*) near the junction of the

[1] F. C. Schrader and A. C. Spencer, House Doc. 546, 56th Cong., 2d sess., 1901, p. 61.

[2] W. C. Mendenhall, *Prof. Paper 41, U.S. Geol. Survey* (1905), pp. 64–65, 72.

[3] *Op. cit.*, p. 61.

[4] Professor T. C. Chamberlin has suggested that this coarse wind-blown deposit from Alaska be called by some such name as Eolian silt or Loess soil, because of the desirability of retaining the term Loess as a structural term rather than one that is purely genetic, especially as a hard-and-fast genetic classification could not be justified historically and presents insuperable difficulty in such a region as China, the great home of the loess, where fluvial loess and eolian loess are most intimately intermingled.

Tanana and Delta rivers in the interior plateau. The samples described and the pictures shown are chiefly from the first of these localities, where the loess soil was clearly exposed in 1910 and 1911 in the new railway cuts.

Lithological character.—Most of the eolian silt or loess is dark brown and made up of fine dust. The color is due to included fragments of vegetation, making the deposit resemble the peaty soil which is also abundant in the region.

Professor B. Shimek, of the University of Iowa, who has been good enough to examine our samples, states[1] that they are not

FIG. 2.—Exposure of loess soil or eolian silt near Chitina, Copper River basin, Alaska, with stump horizons.

exactly physically like the loess of United States, one of them resembling the finest sand which sometimes underlies the loess. This coarseness of the material, which is clearly wind-blown, is what should be expected with the different conditions of loess-accumulation in Alaska and in the Mississippi Valley.

The samples collected in Alaska by the authors have been studied under the microscope by Professor Edward Steidtmann, of the University of Wisconsin. They are made up of particles of various minerals, especially mica, a little feldspar, rare quartz, ferro-magnesian minerals, and some carbonates. There is no

[1] Letter, December 23, 1911.

decomposition of the mineral particles, which are exceedingly angular. Their size varies from .03 to .5 millimeters.

As the loess from the Mississippi Valley averages under 0.0025 to .005 millimeters in diameter,[1] and the maximum size rarely exceeds 0.11 millimeters it is apparent that there must be special reasons why these eolian deposits from the Copper River valley in Alaska are exceptionally coarse. The unusual conditions of deposition of this coarse Alaskan accumulations are explained later (p. 300).

Topography.—The topography of this eolian silt is smooth, molded to the underlying bedrock or drift topography, and never dune-like. The exposures show typical steep cliffs, where cut into by streams and by railway grades. There are many vertical joints and the exposure is, therefore, much like those of the loess in the Mississippi Valley and in other localities in the Middle West.

Thickness of deposits.—The thickness is from a few feet to 40 or 50 feet, and in one case 80 feet. Some of the deeper cuts do not reach the bottom of the deposit. In a few places the bottom of the loess soil is revealed as a sharp contact with glacial outwash gravel or till.

Fossils.—Shells of terrestrial[2] animals are abundant in the exposures, and their presence 20 to 40 feet below the surface and back several feet from the faces of cuts in recent railway excavations is clear evidence that these are the fossils of animals which lived during the period of accumulation of the deposits.

Vegetation.—The included vegetation is well-preserved wood in minute fragments and good-sized logs (Fig. 3). There are also upright stumps of trees, up to a foot in diameter and in some of the thicker deposits those are found in layers several feet apart and one above the other. The greatest number of layers of stumps that we have seen was 7, and as these stumps were all clearly in place, it may be assumed that the wind-blown deposit has accumulated during the time necessary for the growth of 7 generations of trees. The present forest upon the loess surface is thick and mature (Fig. 4). Many of the modern trees are 11 to

[1] T. C. Chamberlin and R. D. Salisbury, *6th Ann. Rept., U.S. Geol. Survey* (1885), pp. 279–80.

[2] Collected in 1911 and determined by Professor B. Shimek.

12 inches in diameter. Some of them show 160 rings of annual growth. As there are 7 or more generations of such buried stumps,

FIG. 3.—Five or six generations of stumps buried in loessian deposit near Chitina, Alaska.

this suggests that the region has been deglaciated at least 700 to 1,000 years as a minimum, for during at least this period the eolian deposit has been accumulating.

Relationships of occurrence.—Most of the localities where loess soil has thus far been observed in Alaska are upon the edges of bluffs or within a mile or two of the rivers. Here vast quantities of gravel, sand, and fine silt are being transported by the present glacial streams, which have rather steep grades and flow 5 to 7 miles per hour. The grade of the main Copper River, for example, averages 7 to 12 feet to the mile, in contrast with the Mississippi and Ohio whose grades average less than half a foot to the mile. The mean annual rainfall in the Copper River basin is about

FIG. 4.—Mature forest growing upon wind-blown deposit, Copper River basin, Alaska.

$36\frac{1}{2}$ inches, only 3 or 4 inches of which come during the summer months when the snow is off the ground. The deposits left by the rivers at low water are, therefore, normally dry and easily blown about by the wind. Severe sand and dust storms are prevalent, indicating the origin of these loessian accumulations in Alaska as wind-blown deposits. We ourselves have witnessed these severe dust storms in 1910 and 1911 and they have been reported by many others from Copper River basin and adjacent regions.[1] Rohn states, for example, that on one occasion in 1899 the material whipped up from the outwash plain "was so thick that it was impos-

[1] Oscar Rohn in *W. R. Abercrombie's Copper River Exploring Expedition, 1899*, Washington, Government Printing Office, 1900, p. 127.

sible to see more than a few rods, and to face it was positively out of the question." Upon the loess-covered surfaces there is, variably, (*a*) thick forest (Fig. 4), (*b*) sparse vegetation, (*c*) grassy slopes, and (*d*) bare soil. Near where the present transportation of the finer material by the wind can still be observed, the grass and trees are notably dusty and there are many dead trees, still standing erect. Doubtless the stumps in the loessian deposits represent trees killed by dust accumulating about their trunks. The preservation of this wood seems to be due to burial in the compact eolian deposit, perhaps in part to the frost, which may also have had something to do with the killing of the trees. The shortness of the stumps seems to come from the fact that the wind blew down the dead tree trunk after it was thoroughly dry, but before it was deeply buried in the loess soil.

The conditions found in the Copper River basin favoring the transportation of dust by the wind and the deposition of eolian silt or loess are: (*a*) abundant water from glaciers, (*b*) much sediment, (*c*) anastomosing branches, (*d*) shrinkage of the streams in the fall and spring when winds are strongest, (*e*) a rather dry climate, and (*f*) dust storms.

In comparison with other areas of similar accumulations the Copper River basin has loessian accumulations as (*a*) terrestrial deposits; (*b*) as in some cases (for example, the Mississippi Valley) associated with glaciation; (*c*) as in some, perhaps all, cases, thickest along rivers; (*d*) coarser than that of the Mississippi Valley. This coarseness may be due to (1) the nearness of the rivers; (2) the violence of the winds here; (3) the coarser sediment carried in the steep-grade streams of Copper River basin as compared with the less steep grade of the Mississippi and its glacial tributaries.

CONCLUSION

The presence or absence of all these drift deposits seems to be chiefly a matter of favorable topography and drainage. The deposition of the loess or eolian silt seems to be directly related to the glacial outwash, to variations of river volume and water level, to the amount of rainfall, and to the winds. Existing deglaciation in the interior of Alaska is apparently a process much like that formerly in progress in northeastern and central United States.

THE UNCONFORMITY AT THE BASE OF THE ONONDAGA LIMESTONE IN NEW YORK AND ITS EQUIVALENT WEST OF BUFFALO[1]

EDWARD M. KINDLE

INTRODUCTION

The importance of stratigraphic breaks has recently been emphasized by a geologist in the following words: "The discovery of such breaks, whether previously suggested by faunal evidence or not, is the most important duty of the progressive stratigrapher."[2] If the demonstration of these breaks is included as a part of the duty of the stratigrapher, most geologists will heartily agree with this sentiment. Stratigraphic breaks not fully supported by evidence have much the same status in geology as have new species which have been discovered but not figured or described. They may or may not be genuine, but in either case they are outside the pale of science until their sponsor has submitted valid evidence of their existence.

The present paper is intended as a contribution to the demonstration and synthetic discussion of a particular unconformity. A stratigraphic break with so great a lateral extent as the one separating the Onondaga and pre-Onondaga sediments merits a more detailed description than it has yet received. The disconformity[3] at the base of the Onondaga limestone, although previously known in western New York[4] and Ontario,[5] has not hitherto been

[1] Published with the permission of the Director of the U.S. Geological Survey and the Director of the Canadian Geological Survey.

[2] *Bull. Geol. Soc. Am.*, XXII (1911), 541.

[3] The term disconformity will be used in the sense proposed by Dr. Grabau (*Science*, N.S., XXIX [1905]) where it is applicable in this paper; but it passes, as will be shown, into a clino-unconformity (Crosby, *Jour. Geol.*, XX [1912], 296) in its western phase. The broader term unconformity is used to include both types of stratigraphic break.

[4] J. M. Clarke, *Memoirs New York State Mus.*, No. 3 (1900), pp. 96–98; A. W. Grabau, *Bull. New York State Mus.*, No. 45 (1901), pp. 117–20.

[5] C. R. Stauffer, *Bull. Geol. Soc. Am.*, (1912), pp. 373–75.

shown to be coextensive with the stratigraphic break at the base of its western equivalents in Ohio and Indiana. It remains to point out the continuity of this break across a wide belt of country extending about 700 miles from eastern New York to the Ohio and Wabash rivers. The Onondaga age of certain sandy beds at the base of the Onondaga limestone in New York which have generally been referred to the Oriskany will also be indicated.

NEW YORK

Eastern and central New York.—The unconformity at the base of the Onondaga though widely extended seems not to have been universal in eastern New York. In southeastern New York there appears to have been no interruption between the Esopus-Schoharie epoch of sedimentation and that of the Onondaga limestone. The fine grits of the former appear, as noted by Van Ingen,[1] to pass very gradually and almost imperceptibly into the impure limestone beds at the base of the latter without any indication of a physical break. There is, too, more resemblance between the fauna of the Onondaga and that of the preceding fine siliceous sediments than could be expected if a physical break had intervened between the periods of their deposition. The presence in the Onondaga of *Anoplotheca acutiplicata*, which is the only common fossil in the Esopus of southeastern New York and adjacent parts of New Jersey, is significant of uninterrupted sedimentation. The failure of many species of the Schoharie to persist into the Onondaga would, of course, be inevitable even with sedimentation uninterrupted, because of the marked difference in the two kinds of sediments and corresponding differences in the conditions under which they were laid down.

While in southeastern New York it appears that the Onondaga limestone sedimentation followed Schoharie sedimentation without interruption of marine conditions, in central and in a portion of eastern New York the evidence is conclusive that the Onondaga limestone was deposited over an extensive area which was submerged shortly before its deposition. Throughout central and western New York there is no trace of the 300 feet of Esopus

[1] *Bull. New York State Mus.*, No. 69, (1903), p. 1204.

and Schoharie formations which, in the Hudson and Delaware valleys, separate the Oriskany from the Onondaga above. In the east-central New York region the Onondaga limestone rests upon an old eroded land surface composed sometimes of the Oriskany sandstone, but much more frequently of limestone of the Helderberg group. The basal beds of the Onondaga if followed westward across New York are seen to rest successively on conformable Schoharie in southeastern New York, disconformable Oriskany sandstone and limestone of the Helderberg group and finally upon Silurian strata in the western part of the state. The physical evidence of the disconformity in this region includes both an irregular or angular contact surface between the Onondaga and subjacent beds and a basal sandstone or conglomerate. The latter is usually less than a foot thick and frequently comprises only a few inches of calcareous sandstone with occasional fragments of limestone from the Helderberg below. This sandy bed at the base of the Onondaga frequently grades upward into the limestone and gradually merges itself into it. The maps and reports which deal with the Devonian in central New York usually refer this basal sandy bed beneath the Onondaga limestone to the Oriskany. There can, however, be but little doubt that it represents reworked Oriskany sand. But it cannot properly be referred to the Oriskany because Oriskany fossils are absent and Onondaga fossils are frequently present in it. This thin basal sandstone band at the base of the Onondaga is well exposed at the Splitrock quarry southwest of Syracuse. At the east end of the Splitrock quarry the 4 or 5 ft. of Onondaga limestone is separated from the Helderberg below by a thin band of sandstone. The lower 2 in. of the sandy beds is probably 75 per cent sand in a calcareous matrix. The percentage of sand decreases and the lime increases upward gradually until all of the sand disappears within 1 ft. of the top of the Helderberg. Only about 6 in. of the sandy band at the base of the Onondaga could properly be called a sandstone and no sharp line of demarkation between this and the slightly less sandy base of the limestone could be drawn. The absence of Oriskany fossils from this basal sandstone and the presence in it of Onondaga corals at the very base of the bed clearly indicate that it belongs

with the Onondaga rather than the Oriskany sediments, as heretofore classed. In places in the eastern part of this quarry the basal bed of the Onondaga includes, in addition to fine sand, flat or oval fragments of the underlying limestone and, more rarely, a rounded pebble of the original Oriskany sandstone. The contact of the sandstone band with the Helderberg is everywhere sharp and clearly defined in marked contrast with the merging contact between the sandy band in the Onondaga above. Sometimes the fine sand penetrates downward into small joints in the Helderberg a short distance. The thin basal sandstone, which I include in the Onondaga formation because of the presence in it of Onondaga fossils, has perhaps its average development at Splitrock. In some areas, however, it is wanting or represented only by a mere film of sand at the contact of the Onondaga and Helderberg. The quarries near Manlius, N.Y., show the minimum development of this sandy band. In some of the Manlius quarries there is no sandstone band at the base of the Onondaga, and fragments of the basal band of this limestone afford no evidence of the presence in them of sand until dissolved in acid, when a small residue of very fine sand is left. The exact line of contact between the Onondaga and Helderberg is easily recognized in the Manlius quarries, where the sandstone is absent, owing to contrast in the appearance of the two limestones. The latter is a fine-textured, hard, dark-blue limestone with few fossils and no crinoid stems, while the Onondaga limestone is a light-gray, coarsely subcrystalline, crinoidal limestone with numerous corals. Some of the corals are of rather large size. One *Favosite* was observed having its base resting on the basal stratum of the Onondaga which has a diameter of 1 ft. Evidence of the disconformity at the contact of these limestones is sometimes distinctly seen in its irregular and angular character, as shown in the photograph (Fig. 1), taken at a quarry one-fourth mile northeast of Manlius. The evenly-bedded Helderberg is here trenched by a shallow troughlike depression about 8 in. in depth, on the side of which the blade of the hammer is seen resting in the photograph (Fig. 1). No trace of residuary clay remains in the Manlius region at the base of the Onondaga, even where eroded depressions like the one shown in Fig. 1 might

be expected to retain it. The Onondaga limestone, however, shows some inclusions in its basal strata of fragments of the Helderberg which were less readily removed by wave action than the subaerial clays which the advancing Onondaga sea must have swept away to other areas. While angular contacts, like the one shown in the figure, are not uncommon, the more usual character of the contact is a horizontal line which affords evidence neither for nor against unconformity with subaerial erosion. It should be pointed out, however, that adjacent disconformable beds, showing no discordance in dip, may have junction over a limited

FIG. 1.—The disconformity between the Onondaga limestone and limestone of the Helderberg group at Manlius, N.Y. The hammer rests on the older formation.

area in a flat plane which represents a considerable amount of subaerial erosion. Even limestones which have experienced the extensive erosion of the present cycle of subaerial degradation in New York may still retain a horizontal upper surface over a limited area. Some of the quarry sections near Manlius, N.Y., show that the contact of the Helderberg and the superposed residuary clay meet along a perfectly horizontal line, although erosion has removed from this particular area many hundreds of feet of rocks.

While the Onondaga limestone rests on the Helderberg, or a thin band of sandstone which, like that at Splitrock, belongs to

the Onondaga over considerable areas in central New York, the Oriskany sandstone is present in many districts. The irregular distribution and great variability in thickness of the Oriskany seem to indicate that the widely scattered patches of the formation represent the remnants of the formation which have been left by the cycle of subaerial erosion which preceded Onondaga deposition. These scattered patches of the Oriskany vary in central New York from 1 ft. or less to 18 or 20 ft.[1] in thickness. The latter thickness

FIG. 2.—Contact of Oriskany sandstone and Onondaga limestone near Jamesville, N.Y. The end of the hammer handle marks the top of the Oriskany and rests upon the etched surfaces of the uppermost band of the Oriskany fossils.

has been reported for the Oriskany on the east side of Skaneateles Lake by Schneider. The contact of the Onondaga and the Oriskany is well exposed in the vicinity of Jamesville, N.Y. In the cliffs near the lake, one-half mile northeast of town, the Oriskany is represented by 30 inches of hard, dark-gray, quartzitic sandstone containing *Spirifer arenosus* and other Oriskany fossils. The

[1] Philip Schneider, *Notes on the Geology of Onondaga County, N.Y.* Syracuse, N.Y.: privately printed, 1894. Pp. 47.

C. C. Wheelock, "The Oriskany Sandstone," *Proc. Onondaga Acad. Sci.*, I (1903). 43.

J. M. Clarke and D. D. Luther, "Geologic Map of the Tully Quadrangle," *Bulletin New York State Mus.*, No. 82 (1905), p. 43.

stratum of the Onondaga limestone immediately above the Oriskany in this section contains a considerable amount of sand, as it does at Splitrock where the Oriskany is absent. The large and numerous Oriskany fossils cease abruptly at a definite plane a little below the top of the arenaceous beds and thus indicate precisely the top of the Oriskany. The sandy element of the basal beds of the Onondaga limestone disappears within from 4 to 10 in. of the top of the Oriskany. The contact of the two formations and the large Oriskany fossils in the lower formation which project beyond the surface of the weathered sandstone are shown in the photograph (Fig. 2). Southwest of Jamesville one-half mile, at the cascade west of the reservoir outlet, the thickness of the Oriskany is about twice that seen in the lake cliffs northeast of town. The section exposed at this point shows:

JAMESVILLE SECTION

	Ft.
Light-gray limestone with corals and other fossils (Onondaga)	7
Hard dark-colored sandstone cemented with lime and holding Oriskany fossils (Oriskany)	6
Thin and evenly bedded dark lead-gray limestone (Helderberg)	15

The Onondaga limestone forms the top and the Helderberg the bottom of the fall. The characteristic chert lenses will be noted in the Onondaga limestone above the hammer in the photograph (Fig. 3).

West of the Finger Lake region the disconformity at the base of the Onondaga eliminates from the section not only the Schoharie and Esopus but the Helderberg as well, letting the Onondaga rest in the western part of the state upon rocks of Silurian age.

Western New York.—The disconformity which marks the break in sedimentation between the Silurian and Devonian systems in western New York is very plainly indicated by both the physical and the faunal evidence in the vicinity of Buffalo. The contact of the Cobleskill and Onondaga limestones is marked by an irregular line in the Falkirk cement quarries and in many other places in the same region. One of the localities where eroded depressions in the Cobleskill may be seen at the base of the Onondaga is in the rock cut of the Lake Erie & Western R.R. near its intersection

with Main Street in northeast Buffalo. Here the abruptly undulating line of separation between the Onondaga limestone and the subjacent Cobleskill is frequently marked by a band of clay or shale a few inches in thickness. In the quarry of the Buffalo Cement

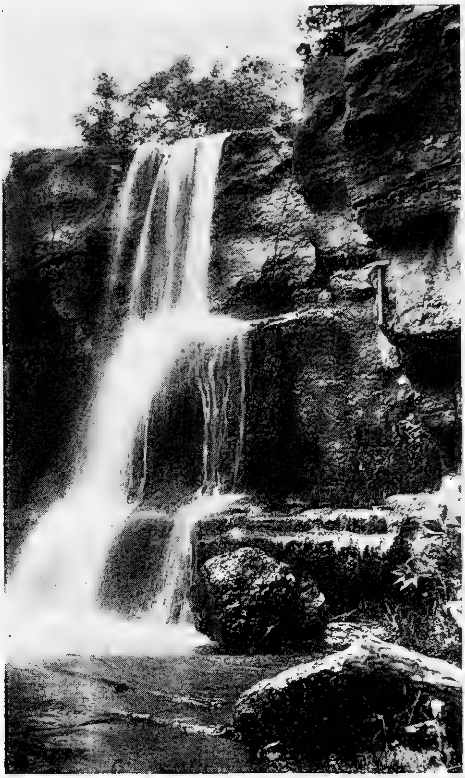


FIG. 3.—Oriskany sandstone and adjacent beds of the Onondaga limestone and limestone of the Helderberg group southwest of Jamesville, N.Y., ½ mile. Lower end of hammer handle marks the top of the Oriskany. The Helderberg forms the foot of the fall.

Company small caverns appear to have been developed in the Cobleskill during the land interval at the end of Silurian time. These contain sand fillings which have been described by Dr. J. M. Clarke.[1] At the cement quarries near Akron a thin band of blue

[1] *Memoirs New York State Mus.*, No. 3, III (1900), 98.

clay or dark shale generally marks the unconformity. The following section just north of Newmans Akron Cement Works will show the character of the unconformity here.

NEWMANS CEMENT WORKS SECTION

	Ft.	In.
Onondaga—		
Limestone and black chert	6	
Gray coralline limestone	4–5	
Dark coffee-colored calcareous shale		2
Corals and dark shale		4
Interformational clay—		
Bluish gray shale, much like clay, with limestone pebbles		1
Cobleskill—		
Drab-colored magnesian limestone	4–6	

Fig. 4 shows the highly irregular and uneven character of the eroded surface of the Cobleskill on which the Onondaga was deposited. At the large quarry, 1 mile northwest of Akron, the stripping of the Onondaga limestone down to the top of the Cobleskill has exposed the upper surface of the latter over a surface of several hundred square yards. This shows admirably the irregular hummocky surface which was covered by the sea during the Onondaga submergence. These inequalities in the surface of the Cobleskill rise above the troughs which separate them from 4 to 6 ft. The surface resembles in its irregularity that which may often be seen where the residuary clay has been stripped from a limestone in the process of quarrying.

ONTARIO AND OHIO

The field observations of the writer on the unconformity at the base of the Onondaga limestone include sections in both Ohio and Ontario. But the recent detailed work of Dr. C. R. Stauffer[1] in these areas on the Onondaga and associated beds will make citation of this author's results, together with some supplementary observations of the writer, suffice for this discussion.

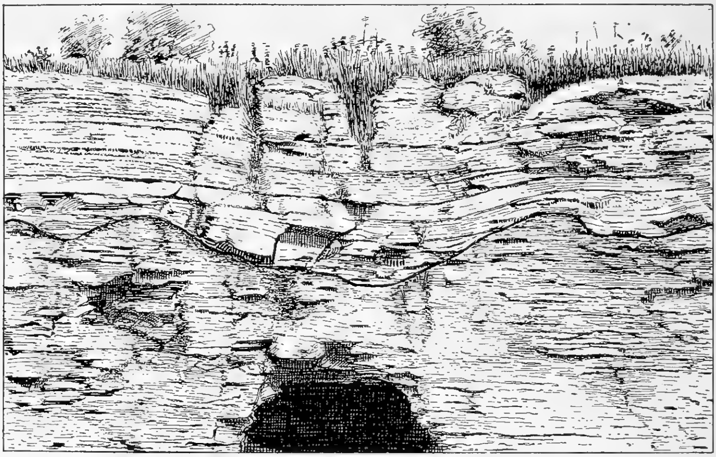
Ontario.—The Onondaga limestone west of Buffalo rests either on the Oriskany sandstone or the Salina formation where the Oriskany is absent as far west as Springvale, Ontario. To the westward of Springvale the Onondaga lies disconformably on a

[1] *Bull. Geol. Soc. Am.*, XXIII, 371–76.

limestone bed in the upper part of the Monroe formation, to which Scherzer, Grabau, and others have applied the name Anderdon limestone. This bed holds a peculiar fauna of supposed Silurian age.[1]

In Ontario the relationship of the Oriskany sandstone to the Onondaga limestone seems to have been misunderstood until very recently. Collections and lists of fossils made by the earlier students of the Ontario Devonian purporting to represent the Oriskany have shown a large proportion of Onondaga species. This has led to the generally accepted view that a fauna existed in

A



B

FIG. 4.—The disconformable contact (A–B) of the Onondaga and the Cobleskill limestones at one of the Akron, N.Y., cement mines. From a photograph.

Ontario which was intermediate in character between the ordinary Oriskany and Onondaga faunas. A new formation name—Decewsville formation[2]—was proposed for the beds holding this fauna. Dr. C. R. Stauffer[3] has recently shown that the "Decewsville" fauna of mingled Onondaga and Oriskany affinities has had its origin in the mixing of fossils from adjacent formations. The relationship of Oriskany and Onondaga formations he has found

[1] *Mich. Geol. and Biol. Surv. Pub. 2*, Geol. Ser. (1910), pp. 42–48.

[2] Ulrich and Schuchert, "Paleozoic Seas and Barriers in Eastern North America," *Bulletin New York State Mus.*, No. 52 (1901), p. 653.

[3] *Bull. Geol. Soc. Am.*, XXIII, 371–76.

to be essentially the same in Ontario as it is in New York. The basal beds of the Onondaga are more or less sandy and approach in appearance the Oriskany sandstone below but contain no Oriskany fossils. The Oriskany sandstone is highly irregular both in thickness and in distribution in Ontario as it is in central New York. It is frequently absent from the sections showing the Onondaga limestone. Where it is present it may thin from a thickness of 15 ft. or more to a few inches in a distance of a few rods. This probably results in large part from the Oriskany sandstone filling troughs of erosion in the Salina formation. The accompanying diagram (Fig. 5) shows the relations of the Onondaga limestone and subjacent Oriskany and Salina formations near Decewsville, Ontario. An excavation about 200 ft. northeast of

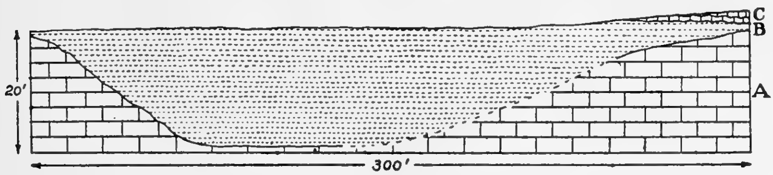


FIG. 5.—Section exposed in vicinity of Oneida Sand Company's quarry, Decewsville, Ont.: A, Salina beds; B, Oriskany sandstone; C, Onondaga limestone.

the Oneida Sand Company's quarry two miles northwest of Decewsville shows the following section:

DECEWSVILLE SECTION

Onondaga limestone	2 ft.	
Oriskany sandstone		17 in.
Limestone (Salina formation)	30 ft.+	

In the quarry less than 200 ft. from the above section the Oriskany sandstone has thickened to nearly 20 ft., as shown in the diagram. Where the Oriskany is absent the Onondaga-Salina contact is doubtless sometimes as irregular as the Oriskany-Salina contact shown in Fig. 5. But the limited number of good exposures and the absence of quarries where the Oriskany is wanting leave the character of the Onondaga-Salina contact to be inferred from the nature of the Oriskany-Salina disconformity. While the physical evidence of the disconformity at the base of the Oriskany

is more striking than that of the stratigraphic break at the base of the Onondaga limestone, evidence of the latter is not wanting. Stauffer[1] states that good-sized pieces of the sandstone containing Oriskany fossils may be found imbedded in the lower part of the cherty limestone, while at other places not far distant the Onondaga rests directly on the Silurian, with only here and there remnants of the Oriskany lying between.

Ohio.—The fauna of the Columbus limestone, which has been listed by Stauffer,[2] affords satisfactory evidence that this limestone is the Ohio representative of the Onondaga limestone. The fauna, lithology, and stratigraphic relations of the Columbus limestone together furnish unmistakable evidence of its identity with the Onondaga limestone. The disconformity at the base of the Columbus limestone has been described by Dr. Stauffer as follows:

> The Middle Devonian of Ohio naturally falls into three divisions, of which the lowermost is known as the Delaware limestone and the upper as the Olentangy shale. This division is based on both lithological and faunal differences which in some respects are more apparent in the vicinity of Columbus, although not wanting in any of the belts of outcrop. . . . .
>
> The base of the Columbus limestone rests upon the Monroe formation; this contact being that between the two great systems, the Silurian and the Devonian. There is thus a great time gap or unconformity, between these two formations, which is strikingly illustrated by the decided change in character and abundance of animal remains. In some localities the lowest layers of the Columbus contain an abundant fauna which in many respects resembles that of the upper part of the same formation, but where these lower layers have been observed in Franklin, Delaware, and Union counties, a basal conglomerate is found which consists of large and small water-worn pebbles of the underlying formation imbedded in a matrix of Columbus limestone. Where this conglomerate is developed few fossils are found; probably because the organic remains, which existed in these localities at the time the layers in question were being deposited, were ground to a shapeless mud by the continuous action of the waves among the pebbles of a rocky coast. This conglomerate was formerly supposed to represent the Oriskany sandstone of New York, and was so mapped by the geologists who made the first county reports, as well as by Newberry himself; but, since this basal conglomerate

[1] *Bull. Geol. Soc. Am.*, XXIII (1912), 373.

[2] C. R. Stauffer, "The Middle Devonian of Ohio," *Bull. Ohio Geol. Survey*, No. 10. (1909), pp. 160–70.

is not continuous and has not been proven to be Oriskany, it has been customary of later years, and perhaps wisely, to drop the Oriskany sandstone from the Ohio scale and include these deposits with the Columbus limestone to which they are at least very closely related.

It will be noted in the description of this disconformity in Ohio that it is characterized locally, as in central New York, by a conglomerate. This is particularly well developed in the central Ohio region near Columbus, where according to Dr. Stauffer[1] decided evidence of the erosion period which intervened is found in the well-developed basal conglomerate of the overlying Columbus limestone.

INDIANA

Ohio valley.—The Columbus limestone of central Ohio and the Onondaga of New York are represented in southern Indiana by a limestone which bears the closest resemblance to them faunally. This formation has been named in Indiana the Jeffersonville limestone. It is the lowest formation of the Devonian as developed at the Falls of the Ohio. This formation has been shown to hold the same fauna and to be the equivalent in the Ohio valley of the Onondaga limestone of New York.[2] It lies between the Sellersburg limestone and the Louisville limestone of Silurian (Niagaran) age. This formation has perhaps its most typical development at the Falls of the Ohio just below the city of Jeffersonville, where it has a thickness of about 20 ft. It is a light- or bluish-gray crystalline or subcrystalline limestone, occurring both as a massive and as a thinly stratified limestone.

The fossil coral reef for which the Falls of the Ohio have long been noted occurs in the lower part of this formation. The important rôle played by corals in the formation of this limestone is indicated by the great size attained by some individuals. One *Favosite* (*F. hemisphericus?*) which was measured has a breadth of 5 ft. and a height of slightly more than 2 ft. *Spirifer acuminatus*

[1] "The Devonian Section of Ten Mile Creek, Lucas County," *Ohio Nat.*, VIII (1908), 273.

[2] E. M. Kindle. The Devonian and Lower Carboniferous Faunas of Southern Indiana and Central Kentucky, *Bull. Amer. Pal.*, No. 12 (1899); The Devonian Fossils and Stratigraphy of Indiana; *Ind. Dept. Geol. Nat. Res.*, *25th Ann. Rept*, pp. 229–763, 31 pls., 1901.

and *Spirifer gregarius* are abundant and characteristic fossils of the upper portion of the formation. The lower part of the Jeffersonville limestone, and the Louisville limestone are well exposed in the Bear Grass Creek quarries just east of Louisville, Ky. The section exposed at the west quarry shows:

LOUISVILLE SECTION	Ft.
1. White to light-gray limestone (Jeffersonville limestone).............	10
2. Light bluish-gray argillaceous limestone (Louisville limestone)........	35

Although all of the sediments and faunas which, in eastern New York, represent the Helderberg group and Oriskany sandstone are missing between the Jeffersonville and the Louisville limestones, evidence of angular unconformity has not been observed in the River sections. Such evidence has been secured a little farther north, however.

North of the Falls of the Ohio 10 or 15 miles, sections which include the Lower Devonian and Niagaran rocks begin to show a thin bed of rather soft, dark-buff to brownish fine-grained magnesian limestone—the Geneva limestone. This formation lies between the Jeffersonville limestone and the Louisville limestone. It thickens gradually toward the north and reaches its maximum development along Flat Rock Creek. The Geneva limestone is generally a massive light-buff to chocolate-brown saccharoidal magnesian limestone. It varies in lithological characters, however. Along Wyloosing Creek, in Jennings County, it is in part a very hard siliceous limestone and was used at one time for mill stones. The fauna of the Geneva limestone indicates that it is of either Schoharie or Onondaga age;[1] probably the former. At the base of the Geneva unmistakable physical evidence of the hiatus between the Geneva and the Louisville limestones has been obtained. An outcrop on the east side of Flat Rock Creek at the ford about $1\frac{1}{2}$ miles above Geneva shows this disconformity. The section exposed at this point is:

FLAT ROCK CREEK SECTION	Ft.	In.
1. Brownish dolomitic saccharoidal limestone (Geneva limestone).....	3	
2. Hard light-gray limestone (Louisville).........................	5	6
3. Blue fossiliferous clay with irregular masses of limestone (Waldron shale)...	5	
4. Hard gray limestone..	15	

[1] E. M. Kindle. *Ind. Dept. Geol. Nat. Res., 25th Ann. Rept.*, pp. 535–58, 1901.

The character of the disconformity between 1 and 2 is shown in the accompanying photograph (Fig. 6). The bed on which the hammer rests is No. 2 of the above section. This disconformity is also seen in the William Avery quarry on the east side of Conn's

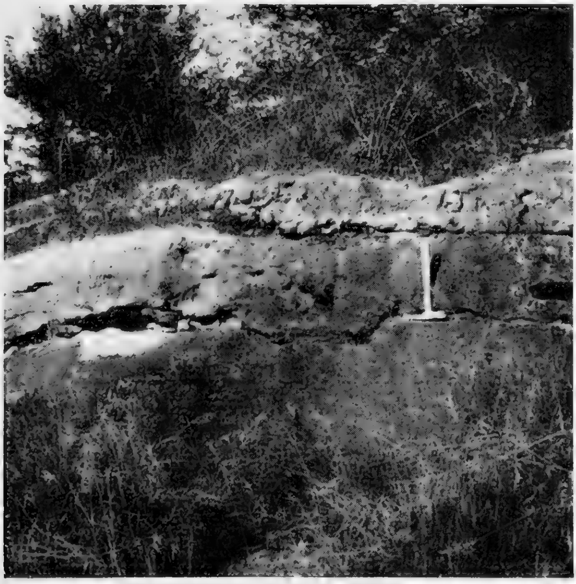


FIG. 6.—The disconformity between the Devonian and Silurian limestones on Flatrock Creek, Shelby Co., Ind. The hammer rests upon the top of the Silurian limestone.

Creek about 1 mile below Waldron, where it is marked by a band of residuary clay in the following section:

CONN'S CREEK SECTION

	Ft.	In.
1. Brownish-buff sandy-looking limestone	2	6
2. Clay		1
3. Blue limestone in 3- to 6-in. layers	5	6

Between the area in the Ohio valley in which outcrops of the Devonian limestone are abundant, and the Wabash valley, where they are also common in a limited district, an extensive drift-covered plain intervenes in which but two or three outcrops of Devonian rocks are known.

Wabash valley.—The Devonian limestones of the Wabash area are differentiated both faunally and lithologically into two divisions, as in the southern part of the southern Indiana area. These two divisions are correlated respectively with the Sellersburg limestone and the Jeffersonville limestone. The Sellersburg formation of the Wabash area contains a Hamilton fauna. It varies from a bluish-drab limestone breaking with subconchoidal fracture to a dark

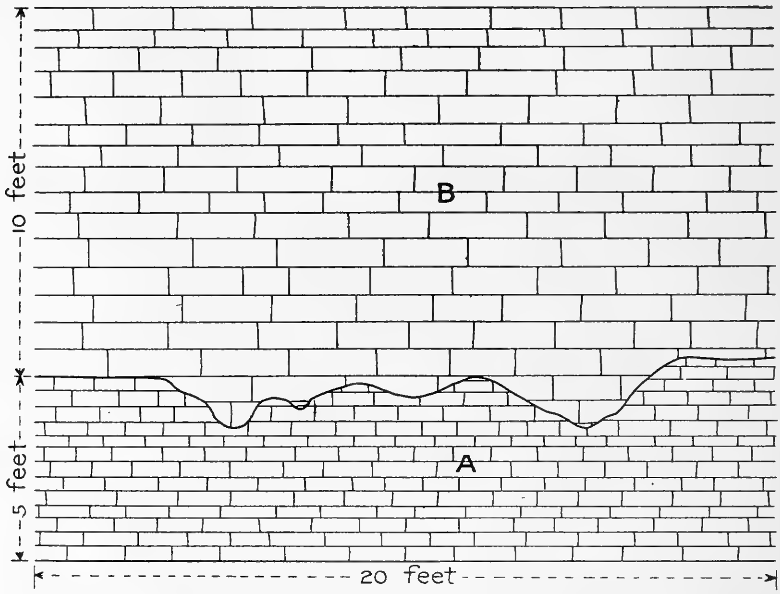


FIG. 7.—Irregular contact line between the Devonian limestone (B) and the Silurian limestone (A) on the bank of the Wabash River, Georgetown, Ind.

argillaceous limestone. *Spirifer pennatus* is the most abundant and generally distributed species.

The formation corresponding to the Jeffersonville limestone at the Falls of the Ohio is a gray crystalline, thin to heavy bedded limestone. This limestone carries a fauna similar to that of the same formation in southern Indiana, and has as one of its most characteristic species *Spirifer acuminatus.* This limestone is unconformable with the Silurian limestone on which it rests. In the other areas in which the stratigraphic break at the base of the Onondaga and its western equivalents has been discussed

there is no discordance in the dip of the strata on the two sides of it, but in the Wabash valley discordance between the Silurian and Devonian limestones is distinctly marked at many outcrops. In this area the term clino-unconformity recently proposed by Professor Crosby[1] is applicable. The Silurian rocks at many points are highly tilted, while the Devonian beds lie nearly horizontal, thus

Fig. 8.—Showing discordance in dip of the Devonian and Silurian limestones at Pipe Creek Falls in northern Indiana.

affording unequivocal evidence of unconformity. Away from the immediate vicinity of the small local domes in the Niagara strata, however, the discordance between the Devonian and Silurian limestones, though slight, can easily be detected with careful observation. Sometimes, however, the discordance is not noticeable.

Just below Georgetown both the Silurian and the Devonian are exposed on each side of the Wabash River. From 5 to 8 ft. of gray crystalline Jeffersonville limestone rests on irregularly eroded Silurian limestone. The line of contact between the two is an

[1] *Jour. Geol.*, XX (1912) 296.

uneven one, frequently rising or sagging on the north side of the river, as shown by the sketch (Fig. 7), but without indicating discordance of dip. On the opposite side of the river the Niagara dips from 6 to 18 degrees to the east, while the Devonian limestone lies horizontal above it, thus indicating deformation as well as erosion previous to the Jeffersonville submergence and showing the relationship of clino-unconformity. The photograph (Fig. 8) indicates this discordance in the dip of the two formations. The Jeffersonville limestone with *Spirifer acuminatus* as its most abundant fossil is the only division of the Devonian here.

The Oriskany sandstone is absent from the Indiana sections. A sandstone known as the Pendleton sandstone resembles it in physical characters, and forms the base of the Devonian section at Pendleton, where it has a thickness of about 7 ft. The fauna of this sandstone, which is wholly unlike the Oriskany, has led to its correlation with the Schoharie grit of New York.

TIME INTERVAL REPRESENTED

The time interval represented by the hiatus at the base of the Onondaga and its western equivalents varies widely in different parts of the area which has been discussed. In the Wabash valley it marks the break between the Silurian and Devonian systems, while in parts of Ontario and New York a far briefer period within the limits of the Devonian system alone is represented. In the western area the time interval may be stated in terms of missing formations. These include the Salina, at the summit of the Silurian, and at the base of the Devonian the Helderberg limestone and the Oriskany sandstone. In New York and Ontario the relationship of the Onondaga and subjacent beds is of the character designated as a disconformity by Dr. Grabau, the beds showing no discordance of dip on the two sides of the unconformity. In northern Indiana, however, there is in some sections distinct though moderate discordance between the unconformable beds, or clino-unconformity.

The place of the longest time interval represented by the stratigraphic break at the base of the Onondaga and its western equivalents as measured by missing formations coincides with the area

in which discordance of dip exists between the unconformable beds. This is limited to the Cincinnati geanticlinal region of northern Indiana. From this area in the Wabash valley of the maximum length of the stratigraphic break at the base of the Jeffersonville limestone, it decreases more or less regularly eastward by the appearance between the Silurian limestone of Guelph age and the Devonian limestone of Onondaga age of the successively younger formations known respectively as the Salina formation, the Cobleskill limestone, the Roundout limestone, the Manlius limestone, and the Oriskany sandstone. With the exception of the last-named formation the western border of each of these lies well to the eastward of the preceding, thus suggesting a shore line retreating eastward during late Silurian and early Devonian time. The distinctive feature of the Oriskany in the New York–Ontario region is its discontinuous character. The western extension to Ontario of Oriskany sediments in irregular patches representing erosion remnants indicates that the easterly retreat of the shore line was reversed about the close of Helderberg time and a submergence of the land occurred in Oriskany time which carried its sediments westward as far as Ontario. Apparently the easterly retreat of the shore line which was reversed with the beginning of Oriskany sedimentation never passed to the eastward of the Hudson River valley in southeastern New York, for no evidence has been found in that region of a stratigraphic break at the base of either the Onondaga or the Oriskany. The disconformity which marks the base of the Onondaga is closely related in space and time with that below the Oriskany.

The erosion of the Oriskany has given it a discontinuous distribution over an area extending from the Hudson River to the middle of southern Ontario. This has resulted in merging the post-Oriskany and pre-Oriskany disconformities into a single disconformity horizon separating the Onondaga and Silurian strata where the Oriskany has been removed.

SECTIONS OF TWO MICHIGAN SALT WELLS[1]

WILLIAM H. FRY
Bureau of Soils, Washington, D.C.

In connection with recent investigations of American salines by this bureau samples from two wells of the Manistee region of Michigan were obtained through the courtesy of Mr. George Abair, of the Peters Salt Co., East Lake, Mich.

All of the samples examined in the preparation of the sections were obtained by drilling, and consequently many of them were in a rather finely pulverized condition. In a number of cases, however, fragments large enough for macroscopic examination were present. In such, the specimens were determined primarily by macroscopic methods. In the cases where all of a particular sample was very finely pulverized, the material was mounted in various oils of definite refractive indices and the mineral constituents determined by the ordinary petrographic methods.

SECTION OF WELL AT LUDINGTON, MICH. STEARNS SALT & LUMBER CO.

No.	Depth in Feet	
19	517– 520	Calcareous sandstone
20	520– 533	Calcareous and shaly sandstone
21–22	533– 573	Calcareous shale
23–24	573– 603	Calcareous and sandy shale
25	603– 608	Calcareous shale
26	608– 609	Sandy calcareous shale
27	609– 615	Buff calcareous and sandy shale
28–39	615– 838	Calcareous shale
40–60	838–1,211	Sandy calcareous shale
61–69	1,211–1,390	Calcareous shale
70–73	1,390–1,463	Limestone (impure)
74–90	1,463–1,801	Fairly pure limestone
91–97	1,801–1,935	Dolomitic limestone
98–102	1,935–2,021	Calcareous mudstone
103–115	2,021–2,281	Limestone
116	2,281–2,290	Halite

[1] Published by permission of the Secretary of Agriculture.

The macroscopic examinations were also checked by this microscopic study. In addition, each sample was subjected to the action of both dilute and concentrated hydrochloric acid, and the character of the effervescence confirmed or modified the previous

SECTION OF WELL 500 FEET FROM EAST LAKE STATION, OF THE PLANT OF THE R. G. PETERS SALT CO.

No.	Depth in Feet	
1	593	Blue calcareous shale
2	597	Calcareous shale
3	800	Calcareous shale
4	978	Limestone
5	1,325	Limestone
6	1,400	Limestone
7	1,425	Limestone
8	1,450	Limestone
9	1,475	Limestone
10	1,487	Calcareous shale
11	1,500	Limestone
12	1,595	Limestone
13	1,605	Limestone
14	1,638	Limestone containing sponge spicules
15	1,645	Calcareous shale containing sponge spicules
16	1,650	Calcareous shale containing sponge spicules
17	1,652	Calcareous shale containing sponge spicules
18	1,656	Calcareous shale
19	1,658	Calcareous shale
20	1,661	Limestone
21	1,680	Limestone
22	1,690	Limestone (rather impure)
23	1,700	Limestone (very sandy)
24	1,762	Limestone (very sandy)
25	1,780	Limestone (very sandy)
26	1,800	Calcareous sandstone
27	1,810	Calcareous sandstone
28	1,820	Limestone
29	1,830	Limestone
30	1,850	Limestone
31	1,862	Limestone
32	1,870	Limestone
33	1,880	Limestone
34	1,895	Limestone
35	1,920	Limestone
36	1,930	Silicious and ferruginous limestone
37	1,940	Silicious and ferruginous limestone
38	1,964	Shaly limestone

examinations. Difficulty was encountered in determining whether some particular samples, especially the finely pulverized samples, should be referred to the limestone or to the shale group. For example, it was found impossible to say absolutely whether a

particular mount was a calcareous shale or a shaly limestone. But predominance of one or the other of the materials was considered sufficient to place a sample, the less abundant material being considered as an impurity and being indicated by an appropriate adjective. Before coming into the writer's hands, the samples had been subjected to a mechanical analysis and all particles less than 0.005 mm. diameter discarded. The amounts of these very small particles, however, were not large enough to vitiate the accuracy of the determinations.

The sections are given in the accompanying tables.

THE HURON AND CLEVELAND SHALES OF NORTHERN OHIO[1]

CHARLES S. PROSSER
Ohio State University

CONTENTS

[1] Published by permission of the State Geologist of Ohio.

INTRODUCTION

Two articles in a recent number of the *American Journal of Science* devoted largely to a consideration of the Ohio shale in northern Ohio[1] appear to make it important that a detailed description of the Huron shale as exposed at its typical locality on the Huron River in northern Ohio be published. This is termed the typical locality because Dr. Newberry stated that "this [Huron] is the shale which forms the banks of the Huron river at Monroeville and below. . . . . The Huron shale in some places contains many concretions of impure limestone, of which hundreds may be seen at Monroeville, where they have washed out of the river banks."[2] Later he wrote: "I have called this in Ohio the Huron shale, because it forms for a long distance the banks of the Huron River, and as it represents several distinct strata in New York and Pennsylvania, it could not with propriety take the name of either of them."[3] Dr. Newberry first published the name Huron shale in 1870 and stated that "its outcrop forms a belt from ten to twenty miles in width, reaching from the Lake shore at the mouth of the Huron River, almost directly south to the mouth of the Scioto."[4]

The area under discussion is shown on the sketch map of Fig. 1 on which the location of the several sections is indicated by an x.

SECTIONS AND DESCRIPTIONS OF HURON SHALE

BASAL DEPOSITS

Slate Cut section.—The banks of the Huron River from Milan down to its mouth at Huron are composed of glacial and alluvial deposits and the base of the shale is not shown on the river. It is exposed, however, in Slate Cut on the Lake Shore & Michigan Southern Ry. about 4 miles northwest of the Huron River and a

[1] E. O. Ulrich, "The Chattanoogan Series with Special Reference to the Ohio Shale Problem," *American Journal of Science*, 4th ser., XXXIV (August, 1912), 157–83. Edward M. Kindle, "The Stratigraphic Relations of the Devonian Shales of Northern Ohio," *ibid.*, pp. 187–213.

[2] *Geological Survey of Ohio*, II (1874), 189.

[3] *Monograph U.S. Geological Survey*, XVI (1889), 57, 58.

[4] "Report of Progress in 1869 (1870)," *Geological Survey of Ohio*, p. 18, or (1871 ed.) 19.

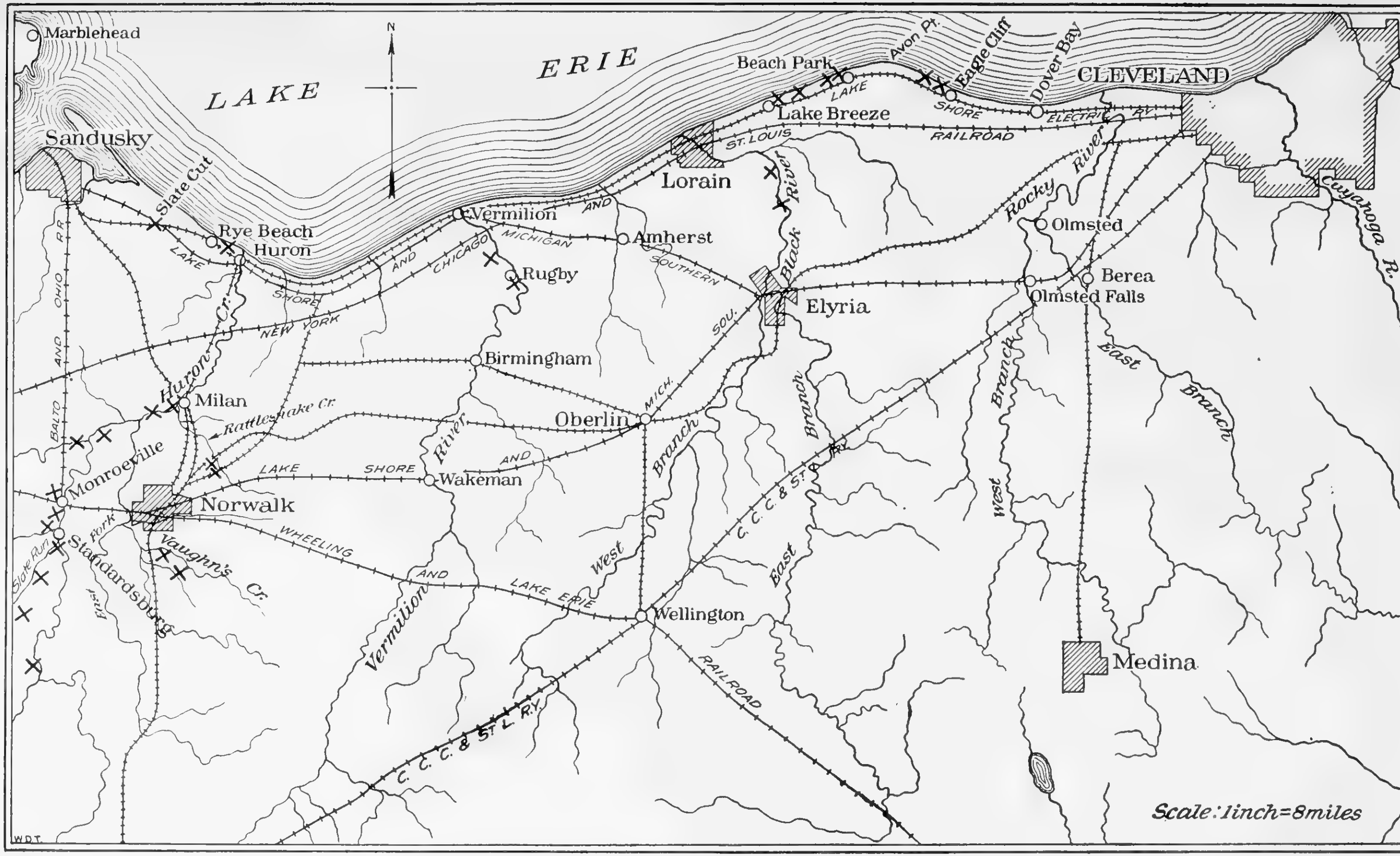


FIG. 1.—Sketch map from Cleveland to the Huron River on which the location of the sections is indicated by the ×-sign

little east of stop 8 on the Lake Shore Electric Ry. The section on the northern bank of the cut is as follows:

Section of Slate Cut	Thickness		Total Thickness	
No.	Ft.	In.	Ft.	In.
4. *Huron shale:* Black, bituminous, hard, slaty shale. At one part of the cut is a bluish-gray lens from $2\frac{1}{2}$ in. to 3 in. thick and in the blackish shale just above are Lingulas. Toward the eastern end and some 5 ft. above the base is a spherical concretion. On this bank 8 ft. 3 in.+ are shown and on the southern 9 ft. 6 in. of shale which does not reach the subjacent limestone	8	3+	10	6−
3. *Prout limestone:*[1] The upper $1\frac{1}{4}$ in. contains a large percentage of marcasite, and the entire layer as weathered is greatly ironstained		3	2	2
2. Rather shaly layer containing crinoid segments and some other fossils		1±	1	11+
1. Massive layer of rather dark gray, dense, and very hard limestone. Contains cup corals, crinoid segments, and some other fossils. The calcareous material of the corals has been largely replaced by silica. Dip of top of this layer between $1\frac{1}{2}°$ and 2°, 20° S. of E. Bottom of cut	1	$10\frac{1}{2}$	1	$10\frac{1}{2}$

This section is shown in Fig. 2 and it has been briefly described by Dr. Stauffer who stated that "the Prout member of the Olentangy is nicely exposed with the overlying Huron shale."[2]

Shore of Lake Erie.—On the shore of Lake Erie about north of the house of Dr. J. P. Esch and stop 15 of the Lake Shore Electric

[1] This name was proposed for the limestone between the superjacent black Huron shale and the subjacent gray Olentangy shale by the writer in October, 1903, and the name published in December of that year (*Ohio Naturalist*, IV, 47). The typical locality is Deep Cut on the Baltimore & Ohio R.R., 6 miles south of Sandusky and about one mile north of Prout, in which 5 ft. of limestone are now shown (see *Geological Survey of Ohio*, 4th ser., Bulletin 10, pp. 119, 120), although in Dr. Newberry's section, which was probably made when the cut was new, it is given as 10 ft. (see *ibid.*, II (1874), 190, No. 2 of section). This limestone is known only in the northern part of the state and it is probably well to consider it as a lentil or member of the Olentangy formation as has been done by Dr. Stauffer (*ibid.*, Bulletin 10, pp. 117, 119, 120 and Pl. IX).

[2] *Ibid.*, p. 122.

Ry., from 4 to 6 in. of black shale are shown. Some of it is more or less mottled with gray lines and splotches and under water is apparently a light-gray layer. The shale must form the bottom of the lake for some distance out from the shore, and numerous spherical concretions partly covered by water occur. These concretions extend along the lake shore for about one-half mile and are about midway between Huron and Rye Beach. This is the

FIG. 2.—Slate Cut showing the upper part of Prout limestone and lower Huron shales. Mr. Roderick stands on top of Prout limestone.

locality where Dr. Kindle, on the authority of Professor E. B. Branson, reports *Dinichthys herzeri* Newb.[1] and which Branson gave as from 50 to 60 ft. above the base of the Huron.[2]

SECTIONS ON THE HURON RIVER

Milan section.—The most northern outcrop of Huron shale, as well as the lowest stratigraphically, on the Huron River is on its western bank a short distance south of the river bridge at Milan

[1] *American Journal Science*, 4th ser., XXXIV, 211.

[2] *University of Missouri Bulletin*, Science ser., II, No. 2 (October, 1911), p. 25.

and $7\frac{3}{4}$ miles south of Slate Cut. The entire length of the bank was studied and the following section prepared after such examination. Toward its upper end, the rocks dip steeply upstream so that the lower part of this section is covered. The lower and middle portions show the lower part of the section. All except the lowest part of the following section was measured near the middle of the bend and the lowest portion farther north.

SECTION ABOVE MILAN RIVER BRIDGE

No.		Thickness Ft.	Thickness In.	Total Thickness Ft.	Total Thickness In.
13.	Black, bituminous, fissile shale which is slaty before it weathers	6	..	18	$10\frac{1}{2}$
12.	Blue shale, 1 to 2 in.	..	$1\frac{1}{2}\pm$	12	$10\frac{1}{2}$
11.	Black shale	..	4	12	9
10.	Blue shale	..	1	12	5
9.	Black shale	..	9	12	4
8.	Blue, argillaceous shale containing disk-shaped concretions	1	6	11	7
7.	Black, bituminous, fissile shale as weathered which is hard and slaty when freshly exposed. Contains large numbers of spherical, calcareous concretions, an occasional somewhat disk-shaped one, and small marcasite concretions. The spherical concretions range in size from 6 in. to 3 ft. 6 in. vertical measurement and from 9 in. to 4 ft. horizontal. They show beautifully the arching of the shale above the concretion and its depression below, indicating their aggregation after the formation of the shale. Stems of probably *Pseudobornia inornata* (Dawson) White were found at 3 ft. 1 in. and 4 ft. 3 in. below the top of this zone, which is believed to be the one in which Dr. Kindle found the long fragment of a trunk of the above species.[1] Zone varies in thickness from 7 ft. 3 in. to 8 ft. 6 in.	$8\pm$	..	10	
6.	Blue to olive, gritty shale, $2\frac{1}{2}$ to 3 in.	..	3	2	1
5.	Black shale	..	$2\frac{1}{2}$	1	10
4.	Blue shale, $2\frac{1}{2}$ to 3 in.	..	3	1	$7\frac{1}{2}$
3.	Black shale	..	$3\frac{1}{2}$	1	$4\frac{1}{2}$
2.	Blue shale, $\frac{3}{4}$ to $2\frac{1}{2}$ in.	..	$2\pm$	1	1
1.	Black shale to river level	..	11	..	11

[1] *American Journal Science*, 4th ser., XXXIV, p. 209.

At the lower end of the cliff only the black shale of zone No. 7 is shown where it is 8 ft. 2 in. thick. For some distance farther up the river the rocks rise so that the zones beneath this concretionary black shale are shown; but after passing the bend they dip down again so that at the southern end of the cliff only the upper black shale is shown. A section at this locality is given by Dr. Kindle in which the 9-ft. zone of "fissile black shale with numerous large spherical concretions"[1] obviously corresponds to zone No. 7 of the above section.

McGue section.—

SECTION ON THE JAMES MCGUE FARM

No.		Thickness		Total Thickness	
		Ft.	In.	Ft.	In.
15.	Bowlder clay and other drift	..			
14.	Blue shale; but entire thickness of zone not shown	..	4±	10+	..
13.	Black shale from $\frac{1}{2}$ to $\frac{3}{4}$ of an in. thick	..	$\frac{1}{2}$+	9	9
12.	Blue shale	..	5	9	$8\frac{1}{2}$
11.	Black shale	..	$2\frac{1}{2}$	9	$3\frac{1}{2}$
10.	Blue shale	..	2−	9	1
9.	Black shale	..	$3\frac{1}{4}$	8	11
8.	Blue shale	..	$9\frac{1}{4}$	8	$7\frac{3}{4}$
7.	Black shale	2	..	7	$10\frac{1}{2}$
6.	Blue shale; toward the lower end of the bank two somewhat irregular-shaped concretions occur	..	$11\frac{1}{2}$	5	$10\frac{1}{2}$
5.	Black shale	..	5	4	11
4.	Blue shale with an occasional very thin layer of black shale near the center	..	$6\frac{1}{2}$	4	6
3.	Black shale	..	3	3	$11\frac{1}{2}$
2.	Blue shale	..	$3\frac{1}{2}$	3	$8\frac{1}{2}$
1.	Black, hard, bituminous, fissile shale which is rather massive and slaty before weathering. Near the top are numerous spherical concretions which were seen only in the upper part of the zone. It also contains marcasite concretions. Two ft. 4 in. are shown where the above section was measured and 3 ft. 5 in. at upper end of cliff, but not reaching the base of the zone	3	5+	3	5+

[1] *Ibid.*, p. 201.

Zone No. 1 of the above section is believed to be the continuation of the black shale at the top of the Milan section (zone No. 13 of that section), but somewhat higher stratigraphically and showing the horizon with spherical concretions which is probably stratigraphically higher than the exposed black shale at the top of the Milan section. Above this zone of rather thick black shale occur alternating zones of blue and black shale which have a considerable total thickness. The next three sections measured in ascending the river, one on the Will Hipteley farm on the eastern side and two on the western side on the Fred Heckelman and Mrs. Helen Andrews farms, do not add very much to the general section of the Huron River; consequently they will be omitted in this article. They are important, however, in tracing the zones shown in the McGue section up the river to the section at Enterprise which will now be described.

Enterprise section.—A steep cliff forms the western bank of the Huron River[1] at the former hamlet of Enterprise below the P. J. Schaffer bridge. The bank is difficult to climb but the following section was measured just below the William H. Newton house by Mr. Tom G. Roderick:

Section of Western Bank of Huron River at Enterprise

No.		Thickness Ft.	Thickness In.	Total Thickness Ft.	Total Thickness In.
21.	Black, hard, bituminous, fissile shale which projects beyond the lower shales as exposed to the north of the middle of this bank. Thickness estimated as from 5 to 6 ft.	5+	..	60±	
20.	Mainly blue, argillaceous shale; but with some layers of black shale from 1 to 3 in. thick. On the high bank on the opposite side of the river, above the Schaffer bridge, disk-shaped concretions occur at about the top of this zone. . . .	32	6	54	9
19.	Black shale.	3	4	22	3

[1] One and three-fourths miles above the Milan River bridge are the forks of the Huron River, which are named West Fork and East Fork on the Sandusky quadrangle of the topographic map. The West Fork is the larger, and in accordance with the usage of Dr. Newberry and at least many of the inhabitants of that region the writer considers the West Fork the continuation of the Huron River and so uses it in this article.

No.		Thickness		Total Thickness	
		Ft.	Ins.	Ft.	Ins.
18.	Blue shale	..	11½	18	11
17.	Black shale	..	10	17	11½
16.	Blue shale	2	2	17	1½
15.	Black shale	..	1½	14	11½
14.	Blue shale	..	6	14	10
13.	Black shale	..	1	14	4
12.	Blue shale	..	4	14	3
11.	Black, hard, bituminous, slaty, fissile shale	2	3	13	11
10.	Blue shale containing irregular more or less disk-shaped concretions	1	..	11	8
9.	Black shale	..	7	10	8
8.	Blue shale	..	7	10	1
7.	Black shale	..	4	9	6
6.	Blue shale	..	3½	9	2
5.	Black, bituminous, hard, slaty, fissile shale containing some large spherical concretions. There are two small ones at almost the top of this zone	7	10½	8	10½
4.	Blue, rather argillaceous shale	..	8	1	..
3.	Black shale	..	2	..	4
2.	Blue shale a little farther upstream than the concretions	..	2+	..	2
1.	River level with rather irregular concretions in blue shale	..	..	..	..

In the above section the black shale containing spherical concretions of zone No. 5 is believed to be the continuation of the lower black shale containing similar concretions as exposed on the western bank of the Huron River on the Andrews, Heckelman, and McGue farms, and then with the upper black shale of the Milan section. Above this black-shale zone are alternating strata of blue and black shale before reaching a blue-shale zone a foot or more in thickness containing irregular or disk-shaped concretions above which is a conspicuous black-shale zone. This black-shale stratum is 2 ft. 3 in. thick in the Enterprise section, 2 ft. 3 in. in the Andrews, 2 ft. 1½ in. in the Heckelman, and 2 ft. in the McGue section. The section by Dr. Kindle "near the bridge 3 miles southwest of Milan"[1] apparently is at or near the locality where the above section was measured.

[1] *Op. cit.*, p. 201.

Farther up the river near the township line of Oxford Township on the Joe Schlacter farm is another cliff on the western bank of the Huron River showing practically a section of the same portion of the Huron shale as the one just described at Enterprise. Very near the base of the section is an 8-ft. zone of black fissile shale containing spherical concretions, which apparently corresponds to zone No. 5 of the Enterprise section, which is 7 ft. $10\frac{1}{2}$ in. thick. Above this black shale in the Schlacter cliff are alternating strata of blue and black shales with a total thickness of 44 ft., when a zone of black shale capping the cliff is reached, 8 ft. or more of which are shown. The corresponding interval between the two conspicuous zones of black shale in the Enterprise section has a thickness of 43 ft. $10\frac{1}{2}$ in.

Seymour Creek section.—The zone of black shale, the lower part of which caps the cliff at Schlacter's and Enterprise, is better shown on Seymour Creek just north of the schoolhouse of Subdistrict No. 6 of Ridgefield Township.

Section of Seymour Creek near Schoolhouse No. 6

No.		Thickness Ft.	Total Thickness Ft.
2.	Black, bituminous, fissile, hard slaty shale. A large globular or spherical concretion is imbedded in this shale, the base of which is about $1\frac{1}{2}$ ft. above the base of this zone. The top of this zone is not shown, but $24\frac{1}{2}$ ft. of the black shale were measured on the bank	$24\frac{1}{2}+$	$52\frac{1}{2}$
1.	Blue shale alternating with thin bands of black shale. In the upper part of the blue shale are numerous large concretions which are lenticular or disk-shaped. There are from 8 to 10 in the vicinity of the bend in the creek and one in the stream is 5 ft. 8 in. by 5 ft. 6 in. A twin one on the bank is 11 ft. long by 6 ft. wide. Five$\pm$ ft. of this zone are shown at this locality and from its top down to the bridge on the lower road there are shown about 28 ft. of the alternating blue and black shales according to a measurement by Professor J. E. Hyde	28	28

This section is shown in Fig. 3, in which the man is indicating with the hammer the contact of the black shale (zone No. 2) which forms the upper part of the bank, and blue shale with thin bands of

black which forms the lower part. Two of the characteristic lenticular-shaped concretions of the soft blue shale are shown a little above water level.

The upper black shale, zone No. 2 of the above section, may be followed up the Huron River to Monroeville, where its top apparently is reached on the bank above the dam and the Main Street bridge; but the writer is not so certain of this identification

FIG. 3.—Black and blue Huron shales on Seymour Creek, the contact indicated by hammer. Spherical concretion in lower part of black shale and lenticular concretions in blue soft shale near water level.

as of that of most of the other zones of this general section. At this locality stems of *Calamites* (*Pseudobornia* [?]) are not infrequent in the black shale of this zone below the Main Street bridge.

Sections in Monroeville and vicinity.—There is a shale bank on the northern side of the Huron River between the dam and Stand Pipe and below the Lake Shore Electric Ry. bridge. The bank was measured near the house of Mr. Rivere Needham, where the following section was obtained:

MONROEVILLE SECTION NEAR HOUSE OF RIVERE NEEDHAM

No.		Thickness Ft.	Total Thickness Ft.
9.	Partly covered upper part of bank. Blue and black alternating shales	8+	$18\frac{1}{2}$
8.	Blue shale	$\frac{3}{4}$	$10\frac{1}{2}$
7.	Black shale	$\frac{3}{4}$	$9\frac{3}{4}$
6.	Dark-blue shale	$\frac{5}{6}$	9
5.	Black shale	$\frac{1}{4}$	$8\frac{1}{6}$
4.	Dark-blue shale, $3\frac{1}{2}\pm$ in. thick	$\frac{1}{4}+$	$7\frac{11}{12}$
3.	Black shale	$\frac{1}{6}$	$7\frac{2}{3}$
2.	Dark-blue shale	$\frac{1}{4}$	$7\frac{1}{2}$
1.	Black shale to water level	$7\frac{1}{4}$	$7\frac{1}{4}$

On the western side of the Huron River above the Lake Shore & Michigan Southern Ry. bridge in Monroeville is a 10− ft.± bank composed mainly of black shale, but with a little blue shale. The upper part of the bank overlying the black shale shows zones of blue- to olive-colored shale, perhaps 6 in. thick, alternating with black shale. Toward the lower end of the bank are numerous rather irregular to lenticular-shaped concretions a little above river level and a little farther up stream similar concretions occur in its bed. This is apparently the continuation of the lower portion of the Needham section; although its stratigraphic position was not determined as accurately as might be desired. The base of the section is vertically probably not more than 8 ft. above the top of the rocks studied below the dam.

One-fourth mile farther up the river and a little below the house of William Schug is a shale bank from 27 (hand-level) to 30 (barometer) ft. high.

SECTION ON HURON RIVER AT WILLIAM SCHUG'S

No.		Thickness Ft.	Total Thickness Ft.
4.	Black shale near top of bank which is considerably broken	2+	27
3.	Blue shales alternating with thin layers of black shale, the blue predominating. In the lower part of the blue shales are large lenticular concretions	$19\frac{2}{3}\pm$	25
2.	Stratum of massive, black shale	$1\frac{5}{6}$	$5\frac{1}{3}$
1.	Black shale alternating with blue to river level, about $3\frac{1}{2}$ ft. thick	$3\frac{1}{2}\pm$	$3\frac{1}{2}$

The shales in the lower part of this bank are dipping upstream (S. 20° W.) at the rate of between 2° and 4°, so that the nearly 10 ft. of black shale shown on the lower bank above the Lake Shore & Michigan Southern Ry. bridge have been carried beneath water level at this locality.

At the three corners, about 1 mile south of Monroeville, is a road quarry where the following section was measured:

SECTION AT THREE CORNERS SOUTH OF SCHUG'S

No.	Thickness Ft.	Total Thickness Ft.
2. Continuous hard, slaty, black shale containing *Protosalvinia* (*Sporangites*)	$10\frac{2}{3}$	16
1. Alternating black and blue shales as shown below the quarry	$5\frac{1}{3}$	$5\frac{1}{3}$

The barometer gave the base of the continuous black shale in the above section as 5 ft. lower than the top of the bank at Schug's. The dip varies from $1\frac{1}{2}°$ to 2°, N. 60° E. The continuous black shale, zone No. 2, of this section apparently is the continuation of the broken black shale at the top of the bank in the section below Schug's house.

Standardsburg sections.—The hamlet of Standardsburg is located on the Huron River $1\frac{1}{2}$ miles south of Monroeville. The black shale on the western bank of the river a few rods above the highway bridge contains two very large concretions and the following section was measured just below the upper one on the land of Mr. William Cook:

SECTION ON HURON RIVER AT STANDARDSBURG

No.	Thickness Ft.	Thickness In.	Total Thickness Ft.	Total Thickness In.
12. Black, hard slaty shale in which are the two very large spherical concretions. The base of the upper one is only 8 in. above the base of this zone. The vertical diameter of the upper one is about 6 ft. and one-half the distance around it is 17 ft. so that its circumference is about 34 ft. This concretion is shown in Fig. 4	5	1	8	$8\frac{1}{2}$
11. Blue shale which is rather hard	..	$6\frac{1}{2}$	3	$7\frac{1}{2}$
10. Black shale	..	$5\frac{1}{4}$	3	1
9. Blue shale	..	$1\frac{3}{4}$	2	$7\frac{3}{4}$
8. Black shale in places split by $\frac{1}{2}$-inch layer of blue shale	..	$2\frac{1}{4}$	2	6

SECTION ON HURON RIVER AT STANDARDSBURG—*Continued*

No.	Thickness Ft.	Thickness In.	Total Thickness Ft.	Total Thickness In.
7. Blue shale	..	$10\frac{3}{4}$	2	$3\frac{3}{4}$
6. Black shale	..	$1\frac{3}{4}$	1	5
5. Blue shale	..	$7\frac{1}{2}$	1	$3\frac{1}{4}$
4. Black shale	..	$2\frac{1}{4}$	..	$7\frac{3}{4}$
3. Blue shale	..	$1\frac{1}{2}$	..	$5\frac{1}{2}$
2. Black shale	..	1	..	4
1. Blue shale to river level	..	3	..	3

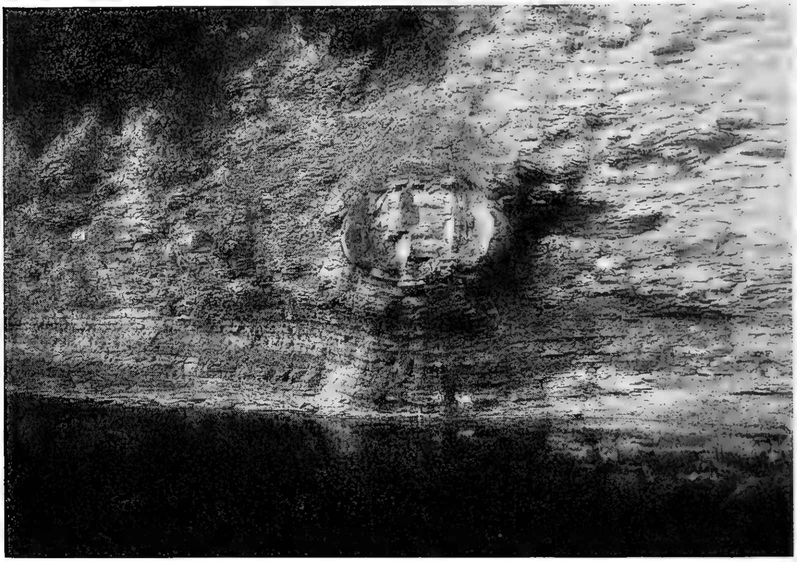


FIG. 4.—Large, spherical concretion in Huron shale on bank of Huron River at Standardsburg.

Zone No. 12 of the above section evidently corresponds to the lower half of zone No. 2 in the quarry at the three corners to the north of Standardsburg. The spherical concretions in the upper black shale at this locality are the largest that the writer has seen in northern Ohio. The black shales show very clearly that they have been moved from their original position by the formation of the concretions, so that the shales are arched above the concretions and correspondingly pushed down beneath them.

A few rods above the section just described, Slate Run enters Huron River from the southwest and near its mouth the south-

eastern bank is steep and rather high. A section of this bank is as follows:

SECTION OF SLATE RUN AT STANDARDSBURG

No.		Thickness Ft.	Total Thickness Ft.
2.	Apparently all hard, black, slaty shale 22 ft. or more thick. No concretions occur in this bank; but farther up the stream where it is crossed by the north-and-south road there is a large spherical concretion in place in the shale and several occur above the creek level	22+	23
1.	Top of blue, slaty shale, which corresponds to zone No. 11 of the previous section, about 1 ft. above water level. Blue shale with black shale below to creek level	1	1

In the bed of Huron River a short distance east of the mouth of Slate Run are large, somewhat lenticular concretions. On the northern bank of the river at this locality, which is opposite the house of Mr. Charles Burgel, from 15 to 18 ft. of hard, black shale are shown.

SLATE RUN SECTIONS

Sections near Pontiac.—On the Huron River to the south of Standardsburg and above the cliff just mentioned, the banks are mainly alluvial and drift. The shales are much better exposed along Slate Run, which is a southwestern tributary of Huron River, and this general section is continued up that run.

The southern bank of Slate Run, at the north-and-south highway bridge and below the railroad at Pontiac, shows 10 ft. of hard, slaty, black shale and below the bridge the bank is higher, apparently showing from 12 to 15 ft. of black shale. The barometer, with an interval of 37 minutes between the readings, gave the level of Slate Run at this bridge as 25 ft. higher than its mouth at Standardsburg. This apparently shows that this black shale is a continuation of the zone forming the greater part of the cliff at the mouth of the run and is probably stratigraphically higher.

Again, where the highway running directly west from Pontiac crosses Slate Run, black shale forms the floor of the stream above the bridge, and below it there is a bank 12 ft. high composed entirely of black shale. The barometer with an interval of 33 minutes between the readings, gave Slate Run as 15 ft. higher than

at the former bridge. This appears to indicate that this zone of hard, slaty, black shale on Slate Run has an approximate thickness of some 50 ft.

Section on Peter Hay farm.—Farther south on the farm of Peter Hay on the western side of Slate Run in Sherman Township is a bank composed of alternating black and blue shales which evidently overlies the one of hard, black shale already described along the lower course of this run. The section begins at the northern end of the bank and continues on up stream as follows:

SECTION OF SLATE RUN BANK ON FARM OF PETER HAY

No.		Thickness		Total Thickness	
		Ft.	In.	Ft.	In.
12.	Drift and alluvial material containing a considerable amount of worked-over black shale ..	8	..	17	6—
11.	Black, shattered shale....................	1	6	9	$5\frac{3}{4}$
10.	Zone more or less disturbed but composed of blue and black shale.....................	2	$5\frac{1}{2}$	7	$11\frac{3}{4}$
9.	Black shale............................	..	$8\frac{1}{2}$	5	$6\frac{1}{4}$
8.	Blue shale.............................	..	$8\frac{1}{2}$	4	$9\frac{3}{4}$
7.	Black shale............................	..	$1\frac{3}{4}$	4	$1\frac{1}{4}$
6.	Blue shale.............................	..	$3\frac{1}{2}$	3	$11\frac{1}{2}$
5.	Black, slaty shale.......................	1	4	3	8
4.	Blue shale containing very irregular concretions of large size. One of them, very irregularly shaped, is 9 ft. long and lies imbedded in the blue shale; another one is about 7 ft. long	1	3	2	4
3.	Black shale, $2\frac{1}{2}$ to 3 in. thick..............	..	3	1	1
2.	Blue shale.............................	..	4	..	10
1.	Black, hard shale at northern end in bed of run..................................	..	6±	..	6

In the above section all the blue shale weathers into small pieces. The layers are more or less disturbed and it is difficult to estimate the dip accurately; but near the southern end it is about 2° to the northeast. Farther up the stream the banks in general are low and alluvial and apparently no shales are exposed that are much higher stratigraphically than those on the Peter Hay farm.

UPPER PART OF HURON RIVER

As already stated, the banks of the Huron River above Standardsburg are generally alluvial and drift. The bed of the river, however, where the east-and-west road west of Macksburg crosses it, is apparently composed of black shale. Again, at the

next bridge to the south crossing the river in the southwestern part of Peru Township and about $1\frac{3}{4}$ miles northeast of Havana, is a bank of slaty, black shale. This bank extends for a short distance on the northern side of the river both above and below the highway bridge and is 10 ft. or so in height. A few rods farther down stream where the river turns to the north is another bank of black, slaty shale on its western side, perhaps a little more than 10 ft. in height. Neither concretions nor layers of cone-in-cone were seen in these banks of black shale. All of the banks farther south on Huron River in Greenfield Township that were visited are composed of alluvial and drift deposits until a point southeast of Steuben is reached where outcrops of Berea sandstone and perhaps Bedford shale occur. Apparently the bank of black shale in the southwestern corner of Peru Township is the last black shale exposed on Huron River and it probably belongs in the Huron.

GENERAL SECTION ON SLATE RUN AND HURON RIVER

A general section of the shales from the upper bank on Slate Run on the Peter Hay farm down this run and Huron River to the lowest outcrop on the river near Milan has been prepared. The section is as follows and the column on the right indicates the location of each zone:

General Section on Slate Run and Huron River

Total Thickness	Thickness of Zone	Location and Description of Zone
0′	10′	Black and blue shale of Slate Run on Peter Hay farm.
10′	50′±	Black, hard slaty shale on Slate Run. Large spherical concretions in lower part.
60′	25′+	Blue and black shales on Huron River at William Schug's.
85′	25′	Black shale from Monroeville to Seymour Creek. Spherical concretions in lower part.
110′	47′	Blue and black shale in Enterprise section. Irregular lenticular to disk-shaped concretions in upper and lower part.
157′	8′	Black shale near base of Enterprise section. Spherical concretions.
165′	3′−	Blue and black shale near Milan. Irregular disk-shaped concretions.
168′	8′±	Black shale containing stems of *Pseudobornia*. Spherical concretions. Lower black shale of section near Milan.
176′	2′	Blue and black shale to river level near Milan. Lowest shale outcrop on Huron River.
178′		

Dr. Kindle states:

The lower part of the black shales above the Olentangy shale is everywhere characterized in Ohio by spherical concretions often of large size. Concretions of this type are entirely unknown in the Cleveland shale both in its typical area and outside of it. On the other hand, in the region where the Cleveland is typically developed the thin limy bands with cone-in-cone structure are common. This type of rock has never been found associated with the spherical concretions. . . . . It is proposed, therefore, to limit the term Huron shale to

FIG. 5.—Huron shale on East Fork of Huron River, below Jacobsburg. Upper part of cliff (15± ft.), all black shale containing spherical concretion near its base with vertical diameter of 5 ft. Blue to bluish-black shale alternating with black from $3\frac{1}{4}$ in. below base of concretion for 9 ft. to river level.

those beds of the Ohio shale exposed on the Huron River, at Rye Beach and elsewhere, in which the spherical concretions occur and the Cleveland shale to the higher beds in which they do not occur and in which the cone-in-cone structure does occur.[1]

In northern Ohio the writer has not seen any spherical concretions in the Cleveland shale or cone-in-cone layers in the Huron shale. In central Ohio, however, thin, limy, lenticular layers with

[1] *American Journal of Science*, 4th ser., XXXIV (August, 1912), 198, 199.

cone-in-cone structure occur at least in the lower part of the Ohio shale, as for example in "the Narrows" and other glens north of Worthington. In the general section of Huron River and Slate Run large spherical concretions occur in the lower part of the highest thick zone of black shale as well as in all the lower zones of black shale with a thickness of 8 ft. or more. It appears certain, therefore, that all of the rocks composing this section belong in the Huron shale. This section perhaps does not include the highest black shale seen on the Huron River in the southwestern corner of Peru Township in which nothing was seen to show whether it belongs in the Cleveland or the Huron shale. This general section does not extend to the base of the Huron shale, which is shown in Slate Cut on the Lake Shore & Michigan Southern Ry. some $7\frac{3}{4}$ miles north of the cliff just above Milan, where the lowest outcrops of the Huron shale on Huron River are shown. The general section gives 178 ft. of the Huron shale on Slate Run and Huron River and the thickness of the mostly covered interval from the lowest outcrops of the section to the base of the formation in Slate Cut is not known. If to the 178 ft. of Huron shale in the general section the thickness of the interval to the base of the formation be added, it will certainly give a thickness of over 200 ft. for the Huron shale on the Huron River. Dr. Kindle estimated that "the Huron will have in the Huron section a thickness of probably 100 feet."[1] A thickness of over 200 ft. for the Huron shale is corroborated by the record of the Citizens' Well, No. 1 at Norwalk, about 5 miles east of Monroeville. The well is located by the side of the Wabash R.R. just east of the Norwalk Gas Plant and its mouth is 40 ft. higher than the level of East Fork Huron River at the old waterworks. The first 85 ft. of the well was in drift,[2] and the Prout limestone which directly underlies the Huron shale in this region was reached at a depth of 288 ft. according to the writer's notes. From a study of the outcrops in the vicinity of Norwalk it appears that the black shale struck in this well at a depth of 85 ft. is strati-

[1] *Ibid.*, p. 199.

[2] Dr. Stauffer in his record of this well gives only 76 ft., composed of samples Nos. 1–5, as drift (*Geological Survey of Ohio*, 4th ser., Bulletin 10 [1909], p. 117); but in the writer's notes on an examination of the samples made on September 11, 1905 he gave samples Nos. 1–6 as drift.

graphically below the base of the Cleveland shale and consequently all of the 203 ft. of shale down to the Prout limestone belong in the Huron shale.

SECTIONS AND DESCRIPTIONS OF CLEVELAND SHALE AND RELATED FORMATIONS

FROM NORWALK TO BLACK RIVER

Sections on Vaughn's Creek south of Norwalk.—As already stated, Dr. Kindle has limited the term Cleveland shale to the higher beds of the Ohio shale in which the spherical concretions "do not occur and in which the cone-in-cone structure does occur."[1] So far as the writer's observations have gone, this appears to be true of the deposits in northern Ohio and he saw no cone-in-cone lenses in the shales on Huron River and Slate Run. The highest outcrops of black shale, however, south and east of Norwalk contain lenses of impure limestone with cone-in-cone structure. The following section on the northern bank of Vaughn's Creek, about $1\frac{3}{4}$ miles south of the court house in Norwalk and a few rods above the Sandusky, Norwalk & Mansfield trolley bridge, was measured:

SECTION ON VAUGHN'S CREEK SOUTH OF NORWALK

No.		Thickness		Total Thickness	
		Ft.	In.	Ft.	In.
18.	Black, hard, slaty shale. Farther up the creek 20+ ft. of this shale are shown with a little cone-in-cone structure	10±	..	25	9
17.	Dark gray shale	..	4	15	9
16.	Black shale	..	6	15	5
15.	Blue shale	..	8	14	11
14.	Black shale	2	2	14	3
13.	Blue shale, from 3 to $3\frac{1}{4}$ in. thick	..	3	12	1
12.	Layer of cone-in-cone, lens-shaped masses thinning out and reappearing again at the same horizon, from 0 to $2\frac{1}{4}$ in. thick	..	2±	11	10
11.	Black shale from $5\frac{1}{2}$ to 6 in. thick	..	$5\frac{1}{2}$+	11	8
10.	Gray shale, from 2 to 3 in. thick	..	$2\frac{1}{2}$+	11	$2\frac{1}{2}$
9.	Black shale	..	3	11	0
8.	Gray shale with some thin layers of black from 16 to 18 in. thick	1	5±	10	9

[1] *American Journal of Science*, 4th ser., XXXIV, 199.

No.	Thickness Ft.	Thickness In.	Total Thickness Ft.	Total Thickness In.
7. Black shale	..	9	9	4
6. Blue, argillaceous shale, from $20\frac{2}{3}$ to 21 in. thick	1	9−	8	7
5. Black shale	..	8	6	10
4. Gray to blue shale	..	4	6	2
3. Black shale	5	0	5	10
2. Gray shale	..	2	..	10
1. Black shale to creek level	..	8	..	8

In the region south and east of Norwalk there is generally a zone of black shale, like No. 18 of the above section, of variable thickness at the top of the Ohio shale, succeeding which, in a few places, is a little of the Bedford shale, but more frequently the Berea sandstone. This irregular thickness of the upper black-shale zone of the Ohio and comparatively little if any of the Bedford formation are due to more extensive erosion before the deposition of the Berea sandstone than occurred in most of Ohio. At part of the localities studied near Norwalk not only is all of the Bedford wanting, but also the upper part of the Ohio or Cleveland shale, so that the Berea sandstone rests on the Huron shale. The writer has described a similar disconformity between the Berea and Bedford formations in central Ohio[1] and in northern Ohio from Rocky River west of Cleveland eastward as far at least as the Grand River Valley,[2] except that the erosion was not so great as in the Norwalk region. There is an example of this disconformity in the immediate vicinity of the section described above. In the bed of Vaughn's Creek and on its northern bank a few rods below the Sandusky, Norwalk & Mansfield trolley bridge is an outcrop of the Berea sandstone at a lower level than the base of the shale section above the bridge. Part of the sandstone is very much contorted with more or less concretionary structure, while some of it is in fairly regular layers. At places there is a bluish, gritty shale below the sandstone and at one point the shale is shown to a depth of 5 ft. and is bluish gray and rather sandy with thin layers of sandstone in it. It is not certain to which formation this shale belongs, although the evidence appears to the

[1] *Journal of Geology*, XX (October—November, 1912), 585–604.

[2] *Geological Survey of Ohio*, 4th ser., Bulletin 15 (1912).

writer to favor its reference to the Berea. Again, a little above the highway and the trolley line, is a knoll a few rods south of the stream, composed of Berea sandstone which shows more or less concretionary structure and ripplemarks. The base of the lowest outcrops in this knoll is $8\frac{1}{2}$ ft. above creek level, while a few rods farther up stream on the opposite bank is the section described above in which the shale runs down into the creek, no sandstone being shown in this section of at least $25\frac{3}{4}$ ft.

In the various sections studied in the vicinity of Norwalk the writer has regarded the upper zone of black shale of the Ohio, No. 18 of the above section, as the western continuation of the Cleveland shale, or at least as representing part of it. It is perhaps a question at what horizon the line of division between the Cleveland and Huron shales is to be drawn; because if all the shale above the lowest layer of cone-in-cone (zone No. 12 in this section) is to be included in the Cleveland, then its lower part will contain some layers of gray to blue shale. If the base of the lowest layer of cone-in-cone in the above section be considered the base of the Cleveland, then it will extend 4 ft. 1 in. below the base of the upper thick zone of black shale.

Farther up the stream, on its northern (eastern) bank and a few rods below the old Cole quarry, the following section was measured. The old quarry is below the highway passing the J. A. Miller house.

SECTION ON VAUGHN'S CREEK BELOW THE COLE QUARRY

No.		Thickness Ft.	Thickness In.	Total Thickness Ft.	Total Thickness In.
11.	Black, hard, slaty shale	18±	..	24	5
10.	Blue shale	..	$1\frac{1}{2}$	6	5
9.	Black shale	1	0	6	$3\frac{1}{2}$
8.	Black shale but much softer than most of it	..	11	5	$3\frac{1}{2}$
7.	Black shale	2	6	4	$4\frac{1}{2}$
6.	Blue shale	..	$3\frac{1}{2}$	1	$10\frac{1}{2}$
5.	Lenticular layer of cone-in-cone varying in thickness from 0 to 3 in	..	2±	1	7
4.	Black shale	..	$6\frac{1}{2}$	1	$5\frac{1}{4}$
3.	Blue shale	..	$2\frac{3}{4}$	..	$10\frac{3}{4}$
2.	Black shale	..	3	..	8
1.	Blue shale to creek level	..	5	..	5

At the upper end of the above section the shales are dipping down stream; but farther down where the high bank of upper black shale occurs they are nearly horizontal. In the above section the base of the lowest cone-in-cone layer (zone No. 5) is 5 ft. below the base of the thick zone of black shale at the top as compared with the 4 ft. 1 in. in the lower section. This bank is apparently the one that Read referred to as some 15 or 20 rods directly north of the Cole quarry, the black shale "in position at the same level [as the quarry]; the strata horizontal and undisturbed."[1] The old quarry was in the Berea sandstone and is apparently another locality on this stream showing channel filling.

Sections on Rattlesnake Creek near East Norwalk.—On Rattlesnake Creek near East Norwalk, about 3 miles northeast of the courthouse in Norwalk, is an excellent section. It is on the eastern bank of the stream a few rods above the Cleveland, Southwestern & Columbus Ry. bridge and the house of Mr. Peter Shoon (spelled Spohn on his mail box). There is a marked anticlinal fold and the following section was measured near the center of the curve in the bank:

SECTION ON RATTLESNAKE CREEK NEAR EAST NORWALK

No.		Thickness Ft.	Thickness In.	Total Thickness Ft.	Total Thickness In.
12.	Hard, slaty, black shale	17±	..	54	5
11.	Soft, olive to blue, argillaceous shale	2	2	37	5
10.	This is probably mostly blackish shale, but not so hard as the upper zone	7±	0	35	3
9.	Mainly soft argillaceous, blackish shale but at base hard, black shale	5	0	28	3
8.	Bluish-gray layer, 3 in. or less in thickness, with rather poor cone-in-cone structure. Higher on the bank is another cone-in-cone layer, but its position in one of the above zones was not determined	..	3−	23	3
7.	Black shale, on the second east bank above this section and about 1½ ft. above the subjacent zone of blue shale, is a more or less concretionary layer of cone-in-cone with a thickness varying from 0 to 3± in	6	0	23	0

[1] *Geological Survey of Ohio*, III (1878), 304.

SECTION ON RATTLESNAKE CREEK NEAR EAST NORWALK—*Continued*

No.		Thickness Ft.	Thickness In.	Total Thickness Ft.	Total Thickness In.
6.	Blue, soft; argillaceous shale containing small rusty concretions, and an irregular, lenticular one	2	3	17	0
5.	Three thin, blue, concretionary, sandy layers separated by blue shale and weathering to a rusty color	..	5±	14	9
4.	Olive shale	1	6	14	4
3.	Black or blackish shale containing a concretionary layer with fairly good cone-in-cone structure. It thins out here and there on the bank but after an interval reappears at the same stratigraphic horizon and varies in thickness from 0 to 1½ in. A thin band of blue shale, 2± in. thick was also noted in this zone of black shale	12	6	12	10
2.	Blue shale containing apparently a very thin layer, ¼ in. or so thick, of blue hard rock with a slight tendency to cone-in-cone structure	..	4±	..	4
1.	Black shale to bottom of creek. These lower two zones and a considerable part of the overlying 12½-ft. zone of black shale are only shown on the lower part of the bank at the axis of the fold	..	..	..	..

In the above section there is a layer of cone-in-cone in the black shale of zone No. 3 and even an imperfect one in the blue shale of zone No. 2; consequently if the layers of cone-in-cone are characteristic of the Cleveland shale, it appears that practically all of the above section is to be referred to that formation. Apparently all of the shale overlying the 2¼-ft. zone of blue shale (No. 6) with a thickness of nearly 37½ ft. ought to be referred to the Cleveland.

Farther up the creek on its western (southern) bank on the Frank Landoll farm the Berea sandstone is shown and the following section was measured:

SECTION ON RATTLESNAKE CREEK ON LANDOLL FARM

No.		Thickness Ft.	Thickness In.	Total Thickness Ft.	Total Thickness In.
10.	*Berea sandstone:* Shaly to fairly massive sandstone, but more or less shattered and highly inclined to the west. The sandstone has more or less contorted or concretionary structure and there is also some shale, from 8 to 10 ft. shown. The lower layer is full of marcasite..	9±	..	46	6
9.	Blue, argillaceous shale lithologically like the Bedford..............................	2	6	37	6
8.	Covered interval........................	1	9±	35	0
7.	Bluish-gray, argillaceous shale lithologically like the Bedford.........................	16	6	33	3
6.	Black, hard shale........................	1	2±	16	9
5.	Bluish-gray, argillaceous shale from $1\frac{1}{2}$ to $2\frac{1}{2}$ in. thick..............................	..	2±	15	7
4.	Black, hard shale........................	1	9	15	5
3.	Bluish-gray, argillaceous, blocky shale lithologically like Bedford.....................	4	0±	13	8
2.	Black, slaty shale lithologically like Cleveland	2	4	9	8
1.	Covered to creek level; but on the opposite bank just below the old stone bridge is black, slaty shale regarded as Cleveland, which contains numerous specimens of *Sporangites*.....	7	4	7	4

In the above section the blue to bluish-gray argillaceous shale of zones 7 and 9 certainly has the lithologic appearance and stratigraphic position of the Bedford. The black shale of zone No. 6 is lithologically like the Cleveland; but below is the 2±-in. layer of bluish-gray shale (zone No. 5), then 1 ft. 9 in. of back shale, (zone No. 4), below which is a 4-ft. zone of bluish-gray shale (No. 3), so that it is somewhat uncertain where the line between the Bedford and Cleveland ought to be drawn. A few rods below the locality of the above section are two abandoned quarries with walls from 30 to 40 ft. high. The barometer indicated that the water level in the first quarry is fully as low as the bed of the creek opposite the section where the base of the Berea sandstone is $37\frac{1}{2}$ ft. above creek level. Mr. Landoll reported that a boring on the bank not far from the above section was all in "slate," no sandstone in it. This is evidently another example of channel filling and others may be seen on the banks of the creek farther up stream.

Vermilion River sections.—The next river east of the Huron is the Vermilion, which also has steep banks affording excellent sections. One of the most interesting is on its eastern bank at Rugby (formerly called Manchester and Mill Hollow), in Brownhelm Township, 18 miles northeast of Milan on the Huron River.

SECTION ON VERMILION RIVER AT RUGBY

No.		Thickness Ft.	Total Thickness Ft.
6.	*Bedford formation:* Near the bend of the river the upper part of the bank is composed of red shale with an estimated thickness of 20 ft	20±	140
5.	Buff to gray argillaceous shale with an occasional thin, harder layer. Measured on roadside up the hill west of the river	10	120
4.	Very hard, gray, fine-grained sandstone which weathers to a brownish color and becomes slightly rotten. Shown in gully on eastern bank just below Bacon Brothers' barn and by highway on western side with a thickness of from 5 to 6 in. Blocks of this sandstone are conspicuous on the steep bank above the Rugby River bridge	$\frac{1}{2}$±	110
3.	Light to dark-gray, blue and buff, soft to rather hard argillaceous shale with a 1-ft. layer of thin-bedded, very compact argillaceous limestone which weathers to brown. Fossils occur in these shales the most abundantly at 3 ft. 8 in. above the base of the zone. The description and measurement for this zone are from the outcrops by the highway west of the river, where it is 6 ft. 5 in. thick	$6\frac{1}{2}$±	$109\frac{1}{2}$
2.	*Cleveland shale:* Black, slaty shale finely shown in river bank above the Rugby bridge. Perhaps there are some lighter-colored layers below the middle of this shale. The bank has that appearance as seen from the opposite side of the river, although it is difficult to be certain. In the gully below the Bacon Brothers' barn there is a covered interval of $13\frac{1}{2}$ ft. from the base of the thin sandstone to the top of the first exposed black shale. From this horizon down to river level at the Rugby bridge is $76\frac{1}{3}$ ft. as leveled by Mr. T.G. Roderick, the writer's assistant. If to this be added the additional 7 ft. of black shale to bring it up to the base of the Bedford as shown on the western side it will make it $83\frac{1}{3}$ ft. Going up the river there is an anticlinal fold which near the bend brings up blue shale, and there are apparently about 8 ft. more of black shale to be added to the bank at the bridge, making altogether $91\frac{1}{3}$ ft. of black shale	$91\frac{1}{3}$	103+
1.	"*Erie shale*" *of Newberry:* Blue shale and thin layers of blue micaceous sandstone, from 2 to 5 in. thick. At bend in river and to river level when water is low	$11\frac{3}{4}$	$11\frac{3}{4}$

Dr. Newberry stated in his description of the Erie shale that "toward the west it rapidly thins out and is lost sight of south and west of the Vermilion river.[1]"

Mr. Bacon stated that Mr. Terrell used to hunt for fossil fishes at this locality; that the largest number of specimens came from the bank above the bridge; that the horizon could be easily reached from the river level and would, therefore, be in the lower part of what is called the Cleveland shale in the above section.

A well was drilled on the Indian Fort farm, at the house of Mr. S. J. Leimbach, $1\frac{1}{4}$ miles south of Rugby, in the summer of 1912. The following data concerning it were furnished by Mr. Leimbach and Mr. Henry Schafer, who drilled it. The sandstone "shell" near the base of the Bedford was struck at a depth of 55 ft. and 7 ft. added to this would give 62 ft. for the depth of the top of the Cleveland shale. The Devonian limestone was reached at 670 ft., above which the driller reported 150 ft. of soft shale. In the well on the F. R. Morse farm, about one-fourth mile north of the Leimbach one, Mr. Schafer stated that there is a streak of bastard limestone 8 to 10 ft. thick about 20 ft. below the top of this soft shale. This hard zone is probably the Prout limestone, in which case the Olentangy shale is 120 ft. thick and 670 ft.–130 ft.+62 ft. leaves 478 ft. for the thickness of the Ohio Shale (Cleveland and Huron shale).

On the western side of the Vermilion River at the Cooper or Miles bridge, a mile below Rugby, is a conspicuous cliff of Cleveland shale. A few rods below the bridge is a gully in which the following section was measured:

SECTION ON VERMILION RIVER BELOW COOPER BRIDGE

No.	Thickness Ft.	Total Thickness Ft.
4. *Cleveland shale:* This zone forms the conspicuous upper part of the cliff and is composed of black, slaty shale. In the gully, where 55 ft. are shown according to the barometer, all black except a one-half inch streak of soft, gray shale. On the highway up western bank near base of continuous black shale a calcareous, gray, lenticular layer 10 to 12 ft. long and about 2 in. thick with cone-in-cone structure....	55±	87

[1] *Geological Survey of Ohio,* I (1873), 163.

SECTION OF VERMILION RIVER BELOW COOPER BRIDGE—*Continued*

No.	Thickness Ft.	Thickness Total Ft.
3. Alternating olive and blue layers of argillaceous shale with black, bituminous shale and thin layers of blue, micaceous sandstone. The light-colored layers of shale predominate	$12\frac{1}{2}$	32
2. Black shale predominates but there are thin bands of light-gray shale with an occasional thin one of blue, micaceous sandstone	$5\frac{1}{2}$	$19\frac{1}{2}$
1. Alluvium to river level	14	14

In the above section there is no evidence to show that the Cleveland shale extends below the base of the 55 ft. of black shale composing zone No. 4. The subjacent shales and thin sandstones may be referred to the Huron shale or its eastern equivalent, the Chagrin formation.

The following section was measured from outcrops by the highway climbing the eastern bank from the Cooper bridge:

SECTION ON VERMILION RIVER EAST OF COOPER BRIDGE

No.	Thickness Ft.	Thickness In.	Total Thickness Ft.	Total Thickness In.
4. *Bedford formation:* Gray, compact, and very hard sandstone, from 6 to 7 in. thick. Farther up the highway is chocolate-colored, argillaceous shale	..	6+	55	0
3. Thin-bedded, blue, impure limestone alternating with shales	1	5	54	6
2. Blue, argillaceous shale in upper part of zone; lower part composed of gray to drab, argillaceous shale	3	1	53	1
1. *Cleveland shale:* Black, slaty shale containing two layers with cone-in-cone structure. The upper one is about 1 in. thick and may be traced for some distance in the shale. Considerably lower and near the base of the outcrop is the other one that is a lens of dark-gray, calcareous rock 8 ft. 10 in. long and near the center 4 in. thick, in which the cone-in-cone structure is well shown. The dip along the highway varies from 4° to 10° N. 40° W. Base of black shale not shown	50±	..	50	..

Black River sections.—To the east of Vermilion River is Black River, which is also bordered by high banks for much of its course northward from Elyria. On the eastern bank of Black River on the farm of the late Mary L. Demeiner (formerly known as the D. W. Garfield farm) in the extreme southern part of Sheffield Township, $3\frac{3}{4}$ miles north of Elyria and $11\frac{3}{4}$ miles northeast of the Rugby section on Vermilion River, is a steep cliff where the following section was measured. Its upper part is exposed by the northern side of the east-and-west highway a few rods below the Demeiner house.

SECTION ON BLACK RIVER ON DEMEINER FARM

No.	Thickness		Total Thickness	
	Ft.	In.	Ft.	In.
5. *Bedford formation:* Soft, rather light-gray, argillaceous shale, 4 to 5 in. shown	..	$4\frac{1}{2}\pm$	71	7
4. Dark-gray to blue, rather blocky shales containing the usual Bedford fauna. The fossils are most abundant in the upper part of the zone and *Parallelodon hamiltoniae* (Hall) is the most common species	1	$9\frac{1}{2}$	71	$2\frac{1}{2}$
3. Soft, light-gray, argillaceous shale from 17 to 18 in. thick	1	6	69	5
2. Coarse, blocky, dark-gray to blackish, arenaceous shale containing some fossils, as *Spirifer* sp. and *Productus* sp.	..	11	67	11
1. *Cleveland shale:* Slaty shale, apparently all black. From river level to base of Bedford 60 ft. by barometer and 67 ft. as leveled by Mr. Charles S. Mead	67	..	67	..

The 67 ft. of black shale in the above section all belong in the Cleveland and the base of the cliff apparently does not reach the top of the Huron or Chagrin shale.

There are steep banks composed mainly of black shale on the sides of the big bend in the Black River east of South Lorain. On the northern side at the "gap" about $1\frac{1}{2}$ miles north of the Demeiner section the bank and outcrops on the highway are apparently all black shale and almost at the base is a calcareous lens $1\frac{1}{2}$ inches thick at the middle, with cone-in-cone structure. These shales contain immense numbers of *Sporangites* which may be collected

in the weathered, loose shales at the foot of the cliff. In the summer of 1912, when this locality was last visited, the river was high so that one could not follow along its lower bank. When it was visited in 1903 it was noted that the western bank shows several small anticlinal and synclinal folds. At a point about opposite the street running west there are 53 ft. of black, slaty shale, apparently all Cleveland, capped by 4 ft. of drift. At the northern end of the cliff near the base it was stated that two layers of micaceous sandstone are brought up, and above these in black shale are at least two bands of soft, olive, argillaceous shale from 2 to 3 in. thick. The lower olive band is about 6 ft. above the upper sandstone stratum. These bands of olive shale are stratigraphically below the base of the 53-ft. bank of black shale and at the northern end of the cliff perhaps 10 ft. of shale stratigraphically lower than the 53-ft. bank are shown.

SHORE OF LAKE ERIE FROM LAKE BREEZE HOUSE TO EAGLE CLIFF VILLAGE

Section near Lake Breeze House.—The lake shore east of the mouth of Black River for nearly 4 miles is said to be composed of drift and soil. Below the grounds of the old Lake Breeze House shales and sandstones appear and the lake shore from this locality eastward is called "iron-bound," on account of the general presence of rock cliffs. The following section was measured on the cliff east of the Lake Breeze House grounds and below the brick schoolhouse in Sheffield Township:

SECTION EAST OF LAKE BREEZE HOUSE

	Thickness Ft.	Thickness In.	Total Thickness Ft.	Total Thickness In.
14. Bowlder clay to top of cliff	10±	..	15	3
13. Black, bituminous shale which on weathering splits up into thin laminae; the edges are rusty with efflorescence of sulphate of iron (melanterite, $FeSO_4 \cdot 7(H_2O)$)	2	10	5	3
12. Soft, gray, argillaceous shale	..	1	2	5
11. Blue, hard, sandy shale	..	1+	2	4
10. Soft, gray shale	..	1−	2	3
9. Blue, compact, very fine-grained sandstone, from 4 to 5 in. thick. Fossil fish in black shale below this sandstone	..	4½	2	2

No.		Thickness Ft.	Thickness In.	Total Thickness Ft.	Total Thickness In.
8.	Black shale from $2\frac{1}{2}$ to $3\frac{1}{2}$ in. thick	..	3	1	$9\frac{1}{2}$
7.	Soft, gray, argillaceous shale containing two thin layers of black shale	..	3	1	$6\frac{1}{2}$
6.	Black shale	..	$1\frac{1}{2}$	1	$3\frac{1}{2}$
5.	Thin layer of bluish sandstone	..	$\frac{3}{4}$	1	2
4.	Black shale	..	$8\frac{1}{2}$	1	$1\frac{1}{4}$
3.	Gray, argillaceous shale	..	$1\frac{1}{4}$	..	$4\frac{3}{4}$
2.	Black shale	..	$2\frac{1}{2}$	..	$3\frac{1}{2}$
1.	Blue to gray, argillaceous shale and base of shale exposed on lake bank	..	1	..	1

Judging from those studied farther east, all of the shales in the above section are below the base of the Cleveland, with the possible exception of the black shale of zone No. 13.

Mr. Charles Maddock, who lives just west of the Lake Breeze House and formerly collected specimens of fossil fish with the late Mr. Jay Terrell at this locality, said that most of the specimens came from the black shale below the thin sandstone layer of zone No. 9. This indicates that those specimens reported by Mr. Terrell from the lake shore near the Lake Breeze House came from the upper part of the Huron shale which farther east is equivalent, stratigraphically, to the upper part of the Chagrin formation.

Dr. Newberry at first referred these fish-bearing shales to the Huron and stated that:

the most interesting specimens found in this locality have rewarded the laborious and intelligent search of Mr. J. Terrell, the proprietor of the Lake Breeze House, situated in the immediate vicinity of the outcrop of the fish-bearing stratum.[1] . . . . These specimens we owe to the enthusiasm and intelligence of Mr. Jay Terrell, who found them at his home in Sheffield, Lorain Co. Here the upper portion of the Huron shale forms, along the Lake Shore, cliffs, which are being constantly worn away by the waves. These cliffs have been Mr. Terrell's favorite hunting ground, and as the erosion of the surface revealed here and there the projecting point of a bone, each indication has been followed up with care, and the bone taken out.[2] . . . . The large number of specimens since obtained, and, indeed, all the remains of *Dinichthys* hitherto taken from the summit of the Huron shale at Sheffield, belong, as we now know, to this species [*D. terrelli*], which is quite distinct from that found at the base of the formation at Delaware [*D. herzeri*].[3]

[1] *Geological Survey of Ohio*, II (1874), 214, also see I (1873), 157.

[2] *Ibid.*, II, Pt. II, Palæontology (1875), 3.

[3] *Ibid.*, p. 4.

Later, Dr. Newberry changed his opinion concerning the age of these fish-bearing shales and wrote as follows:

> This dip misled us, and the thinning of the Erie shale, bringing the Cleveland down near to the Huron, caused these two to be confounded, and led to the supposition that the fish-bearing black shales which form the lake shore in Lorain County were the upper part of the Huron; hence all the great Placoderms discovered by Mr. Terrell were at first referred to that formation. This matter was, however, cleared up by an excursion made by the writer westward from Cleveland in 1886, and it is now definitely established that all the outcrops of black shale in Cuyahoga and Lorain Counties belong to the Cleveland shale, and that none of the fossil fishes described from northern Ohio should be credited to the Huron.[1]

Section on Aaron Hill farm.—The following section was measured at a little gully on the Aaron Hill farm a few rods east of the end of the Harris road and one mile northeast of the Lake Breeze House:

LAKE SHORE SECTION ON THE AARON HILL FARM

No.		Thickness		Total Thickness	
		Ft.	In.	Ft.	In.
11.	Bowlder clay with soil at top	5	..	18	$8\frac{1}{2}$
10.	All black, slaty, bituminous shale. In the shale a lens of coal $1\frac{3}{4}$ in. thick, 3 ft. long, and $3\frac{1}{3}$ ft. above the sandstone layer of zone No. 6	11	5	13	$8\frac{1}{2}$
9.	Blue, argillaceous shale from 1 to $1\frac{3}{4}$ in. thick	..	$1\frac{1}{2}\pm$	2	$3\frac{1}{2}$
8.	Sandstone layer from 0 to $1\frac{1}{4}$ in. thick	..	$1\pm$	2	2
7.	Blue to gray, argillaceous shale	..	$1\frac{1}{2}$	2	1
6.	Blue, compact, micaceous, laminated sandstone layer, from 3 to 6 in. thick, which is the conspicuous one on this part of the lake shore	..	$4\frac{1}{2}\pm$	1	$11\frac{1}{2}$
5.	Black shale from 4 to 5 in. thick	..	$4\frac{1}{2}\pm$	1	7
4.	Soft, gray shale from 2 to 3 in. thick with a streak of black shale at the middle of the zone from $\frac{1}{4}$ to $\frac{1}{2}$ in. thick	..	$2\frac{1}{2}\pm$	1	$2\frac{1}{2}$
3.	Black shale	..	5	1	0
2.	Bluish-gray argillaceous and arenaceous shale	..	1	..	7
1.	Black shale to lake level	..	6	..	6

The above section is about north of the Aaron Hill farmhouse, and a little farther east than opposite his barn the sandstone layer of zone No. 6 is at lake level. This is a dip of $1\frac{1}{2}$ ft. in a horizontal distance of 375 ft. The sandstone reappears in the cliff

[1] *Monograph U.S. Geological Survey,* XVI (1889), 127.

a little farther east than opposite the first farmhouse east of the Hill's. This shows a small synclinal fold and as the shore is followed eastward to Beach Park and beyond there is seen a succession of small anticlinal and synclinal folds as has been described by Dr. Kindle. He states:

With few exceptions these structures have very low arches, nearly flat on top, which rise above their troughs from 3 to 8 feet. The width of these gentle undulations usually ranges between 200 and 350 yards, giving an effect not unlike the billowy surface of a subsiding sea. An exceptionally high arch just west of Eagle Point and another at Beach Park rise 20 feet or more. Detailed study of this lake shore section has shown that the east and west limbs of the series of low anticlinal rolls which succeed each other for more than 8 miles are essentially equal, and that for this distance the base of the Cleveland shale shows no westerly declination between Eagle Cliff and Lake Breeze.[1]

The sandstone of zone No. 6 of the above section is an easy one to follow along the lake cliff as long as it is above water or soon reappears in this succession of anticlinal and synclinal folds. It is a blue to bluish-gray, laminated sandstone which splits up into thinner layers, so that it may be called platy, and when it reaches lake level it breaks out in large rectangular slabs. The main line of joints run about 70° W. of N.

Section on L. B. Ellis farm.—Another lake-shore section was measured on the L. B. Ellis farm, which is about two miles southwest of Beach Park.

LAKE SHORE SECTION ON THE S. B. ELLIS FARM

No.		Thickness		Total Thickness	
		Ft.	In.	Ft.	In.
12.	Black, slaty, bituminous shale. A cone-in-cone lens almost at the base of this zone	6	6	14	4
11.	Soft, gray and blue, argillaceous shale	..	$4\frac{3}{4}$	7	10
10.	Black shale	..	$\frac{3}{4}$	7	$5\frac{1}{4}$
9.	Soft, blue to gray, argillaceous shale	..	3	7	$4\frac{1}{2}$
8.	Black, bituminous shale	..	$\frac{3}{4}$	7	$1\frac{1}{2}$
7.	Soft, blue to gray, argillaceous shale. The total thickness of these gray to blue and black layers of shale between zones 6 and 12 of thick black shale is $12\frac{3}{4}$ in.	..	$3\frac{1}{2}$	7	$\frac{3}{4}$

[1] *American Journal of Science,* 4th ser., XXXIV, 207, 208.

LAKE SHORE SECTION ON THE S. B. ELLIS FARM—*Continued*

No.		Thickness Ft.	Thickness In.	Total Thickness Ft.	Total Thickness In.
6.	Black, slaty, bituminous shale with marcasite concretions	4	10	6	9¼
5.	Soft, blue shale from 3½ to 4 in. thick in which in places near the center of the zone is a little harder material	..	3¾±	1	11¼
4.	Blue, micaceous, laminated, platy sandstone layer, from 2 to 6 in. thick. Both the top and bottom surfaces appear to be uneven so that the thickness of the layer is variable. The conspicuous sandstone layer with numerous loose blocks along this part of the beach	..	4±	1	7½
3.	Black shale	..	3½	1	3½
2.	Soft, blue, argillaceous shale with an inch band of black shale in the center	..	5	1	0
1.	Black shale to lake level	..	7	..	7

The 12¾-inch zone of gray to blue and black shales between zones 6 and 12 of thick black shale shows the appearance of the gray to blue soft shale at a higher stratigraphic position than in the sections toward the Lake Breeze House. For example, in the section on the Hill farm above the conspicuous sandstone zone are from 2½ to 4½ in. of blue, argillaceous shale and sandstone, and then the 11 ft. 5 in. of black shale extending to the top of the shale outcrop. In this section there are from 3½ to 4 in. of blue shale above the conspicuous sandstone, then 4 ft. 10 in. of black shale overlaid by the 12¾ in. of gray to blue and black shale, capped by 6½ ft. of black shale near the base of which is a cone-in-cone layer. This upper zone of black shale, No. 12, certainly appears to belong in the Cleveland.

Beach Park section.—In the western part of Beach Park, just west of the bathing beach, a marked anticlinal fold brings up the rocks for some thickness below the conspicuous sandstone layer, which at this locality appears at the top of the bank until it disappears toward the axis of the fold.

LAKE SHORE SECTION IN WESTERN PART OF BEACH PARK

No.	Thickness Ft.	Thickness In.	Total Thickness Ft.	Total Thickness In.
6. Blue, micaceous, laminated, platy sandstone, which is near top of bank, continues on up to the top and is worn away toward the axis of the fold	..	6	13	$8\frac{1}{4}$
5. Alternating gray to blue, argillaceous and black shale	6	11	13	$2\frac{1}{4}$
4. Blue, thin sandstone from $1\frac{1}{4}$ to 2 in. thick	..	$1\frac{1}{2}\pm$	6	$3\frac{1}{4}$
3. Blue to gray and black shale from 6 to 7 in. thick	..	$6\frac{1}{2}$	6	$1\frac{3}{4}$
2. Blue, thin sandstone from $1\frac{1}{2}$ to 3 in. thick	..	$2\frac{1}{4}\pm$	5	$7\frac{1}{4}$
1. Mainly gray to blue, argillaceous shale with some thin layers of black shale. Lenticular layers of clay ironstone occur in these soft shales, which are like those in the Chagrin formation in the western part of Cleveland. Layer of blue, thin sandstone near base of section. Lake level	5	5	5	5

All of the above section closely resembles lithologically the Chagrin formation as shown along the lake shore to the west of Cleveland and Rocky River. A view of the eastern limb of this anticlinal fold to the east of the bathhouse is shown in Fig. 6.

Avon Point Cliffs.—The blue, conspicuous sandstone was followed in the cliffs bordering the lake to almost opposite the northern end of the road running south to Avon Center, about one-fourth mile southwest of Avon Point. The writer is uncertain whether this sandstone shows or not in the cliffs at Avon Point; but to the east of Avon Point in Avon Lake it has thinned to a somewhat concretionary layer from a fraction of an inch to 2 in thickness. Two ft. or more below is another thin sandstone and 4 ± ft. below that is a zone of three sandstones separated by 8 or 9 in. of shale. Still lower, not far above lake level, are several thin sandstones and the lower shales contain lenticular ironstone concretions. At this locality there are 10 ft. or more of apparently black Cleveland shale forming the upper part of the cliff, below which are some 15 ft.

of blue to gray shale with thin bands of black shale containing layers of sandstone from 1 to 2 in. thick, all of which is referred to the Chagrin formation. This cliff is at the D. E. Parsons cottage in Avon Lake at stop 50 on the Lake Shore Electric Ry. a few rods east of the brick schoolhouse of Avon District No. 4. It is three-fourths of a mile southeast of Avon Point and about one and one-

FIG. 6.—Cliff of Huron shale = Chagrin at Beach Park on shore of Lake Erie, showing one limb of anticlinal fold.

half miles northwest of the western end of Eagle Cliff. The rocks are dipping easterly; but east of Avon Point they lie much more nearly horizontal than to the west of it where there is so much folding.

Section opposite house of John Goetz.—The following section was measured opposite the house of Mr. John Goetz about one mile west of the western end of Eagle Cliff:

LAKE SHORE SECTION OPPOSITE HOUSE OF JOHN GOETZ

No.	Thickness Ft.	Thickness In.	Total Thickness Ft.	Total Thickness In.
12. Drift and soil	3	6	37	10
11. *Cleveland shale:* Apparently all black, slaty, bituminous shale	19	6	34	4
10. *Chagrin formation:* Blue, thin sandstone	..	1	14	10
9. Gray and black shale, alternating	..	11	14	9
8. Blue, thin sandstone from 1 to 1¾ in. thick	..	1½±	13	10
7. Gray and black shale, alternating	2	7	13	8½
6. Blue, thin sandstone from 1 to 2 in. thick	..	1½±	11	1½
5. Soft, gray, argillaceous shale with thin layers of black shale. More or less concretionary layers of thin sandstone occur at irregular intervals	6	9½	11	0
4. Blue, laminated sandstone from 2½ to 3½ in. thick	..	3	4	2½
3. Gray and black shale	..	3	3	11½
2. Blue, thin sandstone from ½ to 2½ in. thick	..	1½±	3	8½
1. Gray and black shale with thin layers of somewhat concretionary sandstone to lake level	3	7	3	7

The 19½ ft. of upper black shale in the above section clearly appear to belong in the Cleveland shale, and the subjacent shales and sandstones the writer refers to the Chagrin.

Section at western end of Eagle Cliff Village.—A mile farther to the southeast the following section was measured at the house of Mr. W. T. Hinz, which is the most eastern one in Avon Township; just to the east is the western end of Eagle Cliff Village of Dover Township.

LAKE SHORE SECTION AT THE HOUSE OF W. T. HINZ

No.	Thickness Ft.	Thickness In.	Total Thickness Ft.	Total Thickness In.
4. Drift and soil	4	..	47	8
3. *Cleveland shale:* Apparently all black, slaty, bituminous shale	34	..	43	8
2. *Chagrin formation:* Blue sandstone and arenaceous shale	..	2	9	8
1. Soft, blue to gray, argillaceous shale alternating with thin layers of black shale. There are also thin layers of blue sandstone. Lake level	9	6	9	6

It will be noticed that the cliffs increase in height as followed eastward from the Lake Breeze House to Eagle Cliff. The cliff at the Goetz house, one mile northwest of Eagle Cliff, is nearly 38 ft. high and the one just west of Eagle Cliff $47\frac{2}{3}$. These higher cliffs also show a greater thickness of the Cleveland shale, as, for example, 34 ft. in the Hinz Cliff, $19\frac{1}{2}$ in the Goetz, and in the low cliffs near Lake Breeze only a few feet at most.

FIG. 7.—Cliff at eastern end of Eagle Cliff Park on shore of Lake Erie. Upper part of cliff Cleveland shale; lower part Chagrin = Huron.

A view of the shore of Lake Erie at the eastern end of Eagle Cliff is shown in Fig. 7, where the upper part of the cliff is composed of Cleveland shale and the lower part of Chagrin = Huron shale.

The cliffs along the lake shore from Eagle Cliff eastward to Rocky River, the banks of this river, the lake shore cliffs in the western part of Cleveland, and many sections on the streams east of Cleveland have recently been described in Bulletin 15, 4th series of the *Geological Survey of Ohio*, to which the reader is referred for a detailed description of these formations in that part of the state.

CONCLUSIONS

It has been shown in Bulletin 15 of the *Geological Survey of Ohio* that the Cleveland shale in the Cleveland region is underlaid by the Chagrin and overlaid by the Bedford formation. The upper part of the Chagrin formation in the Cuyahoga Valley and to the eastward contains a marine molluscan fauna concerning the age of which there appears to be a general agreement that it represents

FIG. 8.—Cleveland shale at junction of East Branch and West Branch of Rocky River at Olmsted.

the Chemung of southern New York which belongs in the upper Devonian. The basal part of the Bedford formation also contains a marine molluscan fauna which has been found as far west as both sides of the Vermilion River and is also present in central Ohio. The weight of evidence also appears to support the reference of this fauna to the Devonian which has been effectively presented in a recent paper by Dr. Girty.[1]

In Bulletin 15 in connection with the present paper, it is shown

[1] *Annals New York Academy of Sciences*, XXI, 295–319.

how, as the Chagrin formation is followed westward from Rocky River along the lake shore and in the stream valleys, that thin layers of black shale appear in the typical blue and gray shales of the Chagrin. These alternating layers of blue and black shales were found in the lower courses of the Black and Vermilion rivers, while on the Huron River, the typical locality of the Huron shale, it was seen that this formation consists of a certain number of zones of practically pure black shale alternating with those that are composed of generally rather thin zones of blue to gray shale alternating with black shale. The formation has a thickness of over 200 ft. in the Huron River region and the thick zones of black shale contain spherical concretions of variable size. The invertebrate, vertebrate, and plant fossils contained in the Huron shale are of Devonian age according to the opinions of at least most paleontologists who have recently studied them.[1] The Cleveland, composed mainly of black, bituminous shale containing lens-shaped layers with cone-in-cone structure and without spherical concretions, overlies the Chagrin formation in the Cleveland region and on Rocky River, while to the west in other streams or in the cliffs of the lake shore nearly, if not quite, as far as Lake Breeze it overlies the alternating blue to gray and black shales with thin sandstones. The Cleveland shale overlies similar alternating shales in the Black and Vermilion river valleys and the Huron shale in the Norwalk region. The thickness of the Bedford formation is variable in all this region, largely due to the erosion of its upper surface before the deposition of the Berea sandstone, which was perhaps in general greatest in the Norwalk region where frequently all of the formation is wanting and at most only the lower part remains. The Bedford fauna and the disconformity between the Bedford or Ohio shale and Berea formations favors drawing the line of separation between the Devonian and Mississippian at this horizon. It appears clear that the upper black shale crossing this district is the Cleveland, that the Huron shale in general is the western lithologically more or less changed stratigraphic equivalent of the Chagrin formation, and that both the stratigraphic and paleontologic evidence agree in referring it to the Devonian.

[1] For a summary of these opinions see *Geological Survey of Ohio*, Bulletin 15, chap. vi, 509–29.

OSTODOLEPIS BREVISPINATUS, A NEW REPTILE FROM THE PERMIAN OF TEXAS

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University of Chicago

In the summer of 1909 the writer found, on West Coffee Creek in Willsbarger County, Texas, a series of seven articulated vertebrae and their connected ribs, for the most part concealed in a small block of red sandstone. At the time of their discovery a new genus of reptiles was recognized in the specimen, but only recently has the opportunity for its further examination presented itself. The removal of the concealing matrix has revealed certain unique characters that will justify the description of the well-preserved, though incomplete specimen.

The vertebrae resemble those of *Araeoscelis* more closely than those of any other form hitherto made known from the Permocarboniferous deposits of America. They also seem to resemble those of *Tomicosaurus* Case, so far as their arches are concerned—the centra are unknown in the latter genus—but differ in the presence of stout diapophyses and much greater size. The centra of *Ostodolepis* are as broad as long. The ends, as usual, are deeply and conically concave, with a small perforating foramen. The under side is gently concave longitudinally, broad from side to side, and gently concave in the middle transversely. Just above the sides of the nearly square under surface there is a shallow lateral fossa near the middle. The arch is low and flattened, broad from side to side, though not at all cotylosaurian in character, and has a very small, almost vestigial, tuberculiform spine. The zygapophyses are broad and flat, and their articular surfaces look almost directly upward and downward. On the lower part of the arch on each side, near the front end of the vertebra, there is a rather stout, but short, diapophysis, directed outward and a little downward and backward, with its free end oval in outline and gently cupped. Unlike any centra from Texas hitherto

observed by the writer, those of the present specimen on their free surface show numerous, irregularly placed, minute pits leading into nutrient canals.

The ribs, for the most part, are preserved in position. Each has a rather prominent and stout tubercle lying in apposition with the end of a diapophysis; and the capitulum lies in the intercentral space below the middle of the vertebra, and near the end of the very slender intercentrum. The fractured ends of the ribs show a small central cavity filled with crystals.

The block of matrix, as discovered, showed along its fractured edges, nearly parallel with the under side of the vertebrae, two series of overlapping, slender, bony lines, which were first supposed to be merely imbricated ventral ribs, though the absence of fractured ends was inexplicable. When the lateral surfaces were cleared of matrix these lines were found to be the fractured edges of bony plates. These lines lie along the broken edge of the block in very orderly arrangement, their inner, posterior ends about one millimeter apart; they are directed obliquely forward and outward. Each line measures about eight millimeters in length, and is of about the thickness of writing paper; they lie closely upon each other and are straight. The external, anterior, and very thin margins of these scutes are directed forward, a remarkable arrangement. None of the scutes can be laid bare completely, but the numerous ones seen on the surface below the vertebrae show a width of each approximating its length. The angles are broadly rounded. The outer surface seems to show shallow concentric grooves, possibly corresponding to the free margins of the overlying scutes, of which there are about six. Under a hand lens they show very distinct, slender raised lines, quite concentric with the free margin. In general the scutes resemble the cycloidal scales of bony fishes.

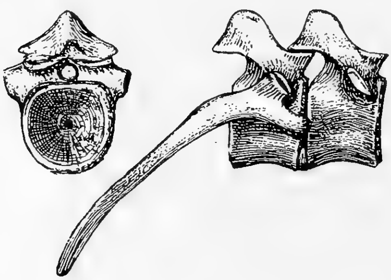

FIG. 1.—*Ostodolepis brevispinatus* Williston. Posterior dorsal vertebrae from the side and in front, with articulated rib. Natural size.

The surface showing these scutes, as exposed on each side, is about an inch and a quarter in width, and must have been originally at least a half-inch wider. The scutes continue quite to the vertebrae, ascending a short distance on their sides, and over the ends of the posteriorly directed ribs. It would seem very probable that, after decomposition of the body had begun, the skin bearing these scutes had slipped down from the ribs and vertebrae till it came nearly in contact on the two sides. No trace of the scutes, however, was found in the matrix over the arches of the vertebrae.

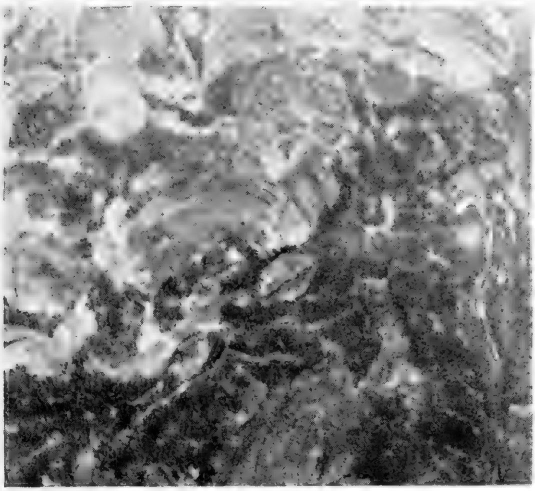

FIG. 2.—*Ostodolepis brevispinatus*. Scutes of right side. Enlarged.

Whether or not these scutes originally covered the whole of the body can not be determined in this specimen, though it is quite evident that they covered the whole under surface of the abdomen as high up as the vertebrae, in the living animal. The vertebrae are evidently from the posterior dorsal region. Such bony scutes, whether they be ventral only or not, are wholly unlike anything that has hitherto been observed among the Permocarboniferous reptiles of America, and very unlike the slender ventral ribs which have been observed in other genera, such as *Labidosaurus*, *Captorhinus*, *Poecilospondylus*, *Varanosaurus*, *Ophiacodon*, etc. In all

these genera these ribs appear to be continuous, directed backward, outward and upward from the median line back of the coracoids, and they are not at all imbricated. In this remarkable specimen they lie everywhere in five or six imbricated layers directed obliquely forward and outward, the thin external edges about one millimeter or a little more apart. Such an arrangement, if they be dermal structures, must certainly have been inconvenient for a crawling creature, unless it were descending a tree! And this leads to the conclusion that these scutes, notwithstanding their close imbrication and fish-like appearance, must have been ossifications in the connective tissue, and overlaid by the skin in life.

The very short spines, the broad and flat zygapophyses and strong rib attachments suggest a slender lizard-like form for the living animal, one probably with long legs and prehensile feet, cursorial or climbing in habit.

The name *Trispondylus* Williston (this Journal, XVIII, 592) is preoccupied; it may be replaced by *Trichasaurus*, nom. nov.

NOTE ON THE GEOLOGY OF THE ISLE OF PINES, CUBA

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It was the good fortune of the writer to be one of a party constituting an expedition of the Carnegie Museum to the Isle of Pines during the month of May, 1910. While primarily busily engaged in collecting and studying the flora of the island, the writer incidentally noted certain geologic features of the island some of which are erroneously reported in our present literature.

The Isle of Pines is situated about 65 miles south and a little west of Batabano, a small seaport on the south coast of Cuba almost directly south of Havana. The area of the island is approximately 1,200 square miles and it is divided by an east-west swamp into an irregularly oblong northern portion measuring about 30 miles east and west and a narrow southern portion about 40 miles long, east and west, with its western end tapering out and upcurving toward the northwest for a considerable distance beyond the remainder of the island. The general features of the northeastern and central portions of the island are well described by Hayes,[1] who notes that the island "consists essentially of a level plain above which rise numerous isolated ridges. The plain itself consists of three distinct elements: (1) a low coastal fringe, (2) elevated terraces, (3) interior plain."

The writer can add little to Hayes's description of the portion of the island covered by the latter; but the lower valley of the Río de las Nuevas was explored to its mouth in the extreme northwestern point of the island, and it may be added that here the shallow sea is being rapidly reclaimed through the agencies of the mangroves and the alluvial materials washed down by the river. This river is the largest one in the island and for several miles back from its

[1] "Report on a Geological Reconnoissance of Cuba, Made under the Direction of General Leonard Wood, Military Governor, by C. Willard Hayes, T. Wayland Vaughan, and Arthur C. Spencer, Geologists, 1901," *Annual Report* of Brig.-Gen. L. Wood, Military Governor of Cuba, 1901. Vol. I.

mouth the whole surrounding region can be seen to have been rescued from the sea by the united efforts of the river and the mangrove.

The twenty-mile trip from Nueva Gerona to Los Indios, on the western coast of the island, was made by automobile, going south from McKinley across the level and fairly fertile plain constituting the upper drainage basin of the Río de las Nuevas. The ridge forming the divide between this river and the rivers draining toward Los Indios was found to have rather easy slopes, with but little rock exposed, this rock being a quartz-mica schist. Toward Los Indios we soon dropped to a slightly elevated level plain whose surface in places consisted of considerable areas of glistening white angular quartz pebbles and was almost bare of vegetation. As noted by Hayes, there is considerable iron lying about in places, evidently left after the erosion of the soft schist. Much of this surface iron was noted in a trip made from Los Indios to the highest point of La Cañada range about 6 miles west of the town.

The Sierra de la Cañada was supposed by Hayes[1], judging from its topography viewed from a distance, to be of the Gerona Marble; but the ridge is made up of quartz-mica schists, distinctly banded, with a general northeast dip. The southwestern exposure is quite steep and precipitous and probably owes this character to wave-cutting during a past period when the land stood at a different level, as is so clearly shown around the bases of the marble mountains in the northeastern part of the island. The top of the ridge was found to attain a height of 985 feet, by barometer, and access was fairly easy by following up the ravines and along the rather gentle slopes of minor ridges. The whole ridge is covered by a sparse pine and star-palm vegetation wherever the plants can get a foothold. At the base of the steeper side of the ridge is a well-developed talus slope, and from this stretches away immediately the quite level sandy or gravelly plain, pine-covered clear to the coastal fringe. Willis, in his "Index"[2] has unfortunately accepted the erroneous supposition as to the character of the Sierra de la Cañada.

[1] *Op. cit.*, p. 114.

[2] Bailey Willis, "Index to the Stratigraphy of North America," *Professional Paper 71, U.S. Geol. Surv.*, 1912, p. 349.

From Siguanea City the writer, in company with Col. T. J. Keenan and Dr. T. D. Atkinson, made the trip across Siguanea Bay to the peninsula extending out from the southwestern corner of the island. Here the bottom of the bay shallows very gradually out to the low shore and apparently the same general rise continues clear across to the "south coast," a distance of three miles or more. The surface of this part of the peninsula consists of a hard "coral" limestone in the little pockets of which a rich humus soil has collected and which thus supports a rich, broad-leaved vegetation. On the "south coast," at Caleta Grande, the sea was beating against a very rough and jagged coast with a cliff which in many places reaches a height of 80 or 90 feet. A narrow shelf projects out into the sea at a slight depth, bearing numerous projecting jagged rocks, and from this shelf the sea deepens very rapidly to the south. The surface of the coral limestone of this peninsula appears to have about the same general northeast dip as was seen in the Sierra de la Cañada.

Reviews

Geology.—Reconnaissance of the Jarbidge, Contact and Elk Mountain Mining Districts, Nevada. By F. C. Schrader. Bull. U.S. Geological Survey No. 497, pp. 162, with maps, sections, and illustrations. 1912.

Geography.—The districts are in Elko County in northeastern Nevada near the Idaho state line. They are contained in an east-west rectangular area about 35 miles long by 26 miles wide, the Jarbidge district being in the western part, the Contact district in the eastern part, and the Elk Mountain district in the northern part. Geologically and mineralogically the Elk Mountain district is a small-scale replica of the Contact district.

The area is about 50 miles distant from the Twin Falls Branch of the Oregon Short Line Railroad on the north and from the Southern Pacific Railroad on the south. It lies in the northeastern part of the upland region known as the Nevada Plateau. It is mainly on the southern rim of the Snake River drainage basin, whence it extends across the divide and includes a small part of the adjacent Great Basin on the south. It lies at the general elevation of about 6,000 feet, but it is mostly mountainous and has a vertical range of nearly 6,000 feet and culminates at about 11,000 feet in the Jarbidge Mountains on the west. In the western part the drainage issues northward through the Bruneau River, and in the eastern part easterly, thence northward through the Salmon River, both rivers being main south-side tributaries of the Snake.

Geology.—The area is in a region of fundamentally Paleozoic sedimentary rocks seemingly Carboniferous. They consist principally of quartzite, limestone, shale, and slate, folded, faulted, intruded by Cretaceous (?) granodiorite, flooded and capped by Tertiary eruptives, principally rhyolite, and overlain by Tertiary lake beds and Quaternary gravel and alluvium.

In the Jarbidge district the rocks are principally rhyolites. Here the Paleozoic sediments are exposed only on the west. They consist, in ascending order, of quartzite, limestone, and shale aggregating about 3,000 feet (?) in thickness and they dip steeply to the north. The rhyolites are separable into two distinct groups, old rhyolite of Miocene (?) age

and young rhyolite, Pliocene. Each consists of a series of superimposed flows.

The old rhyolite occupies a central area about 8 miles square, has a thickness of nearly 5,000 feet, and is the principal ore-bearing rock. Its flows are heavy, ill defined, and lie nearly horizontal. It is gently folded, faulted, and considerably fissured. It is coarse textured with large phenocrysts of wine-colored quartz and feldspar.

The young rhyolite surrounds the old rhyolite with wide extent. It has a maximum thickness of nearly 2,000 feet. It is non-ore-bearing and but little disturbed. Its flows are relatively thin, well banded, and dip gently outward. It is lithoidal or aphanitic with little or no visible quartz, the silica occurring mainly in the form of tridymite.

The principal rocks of the Contact district are the granodiorite and the Paleozoic sediments which it intrudes. The granodiorite occupies a central elongated quaquaversal east-west batholitic belt 25 miles long by 6 miles wide. Surrounding it in a belt several miles in width succeeds the overlying quaquaversally outward dipping Paleozoic sediments with a known thickness of about 1,600 feet. They are considerably contact metamorphosed by the magmatic intrusion of the granodiorite and both they and the granodiorite are intruded by complementary syenitic, aplitic, lamprophyric, and monzonite dikes. The rhyolite which occurs chiefly peripherally corresponds to the young rhyolite of the Jarbidge district with which it seems to be continuous. The old rhyolite of that district seems to thin and peter out on the western headwaters of the Salmon and does not appear in the Contact district.

The Tertiary lake beds of the area occur chiefly in low places in the Contact district where they have a known thickness of 400 feet. They are mainly gray "sandstone" composed of volcanic tuff which is chiefly pumiceous. In places they are tilted, flexed, and gently folded. They seem to be of Pliocene age and belong to the Humboldt formation.

The Quaternary deposits of the area include in the Jarbidge Mountains, besides recent stream gravels, débris, and wash from the hills, also some glacial accumulations of Pleistocene age.

Ore deposits.—The ores were deposited in at least two distinct periods of mineralization, Cretaceous (?) and post-Miocene.

The Cretaceous (?) deposits are chiefly auriferous and argentiferous copper ores. They occur mainly in the Contact district and consist principally of contact metamorphic deposits conforming to the contact zone of the granodiorite with the Paleozoic sedimentaries, and deposits in fissures. The contact metamorphic deposits contain much axinite,

indicating that pneumatolitic action was an important agency in their origin. The fissure deposits are associated with the complementary dikes and contemporaneous or slightly later quartz veins, and include replacement deposits in the wall rock. They occur principally in the granodiorite. The fissures have a steep southerly dip.

The post-Miocene deposits are argentiferous gold ores. They occur in quartz-adularia fissure veins in the old rhyolite in the Jarbidge district. They were discovered late in 1909. The fissures are mostly contained in two main systems which converge downward. Those of the west system dip steeply to the east and those of the east system dip steeply to the west. The gangue is pseudomorphic after calcite and rhyolite and was deposited by ascending thermal solutions that dissolved out and replaced the earlier calcite gangue.

Sandstone of the Wisconsin Coast of Lake Superior. By FREDERIK TURVILLE THWAITES. Bull. No. XXV, Wisconsin Geol. and Nat. Hist. Surv. Pp. 117+viii. Plates XXIII. Madison, 1912.

The stratigraphic relations and geologic age of the red sandstones of the Lake Superior region have long been a subject of discussion arising from the fact that the older sandstones are closely allied to the Keweenawan while the younger beds partake more of the general characteristics of the Cambrian. The older sandstones are characteristically composed of arkose material and the strata are nearly always tilted. The younger group is almost wholly quartz sandstone, and its beds are generally horizontal. Both series, so far as known, are entirely devoid of organic remains. Former investigators recognized that the lower group was a part of the Keweenawan series, but opinions differed as to its relation to the upper; some held that the two were conformable, while others maintained that an unconformity existed and that the upper group probably corresponded to the Cambrian of southern Wisconsin, or its conformable downward extension.

One of the principal results of the present study was the conclusion that the upper quartz sandstone grades conformably downward into red shales and arkose sandstones which possess the same characters as the main body of the recognized Keweenawan sediments. As no conclusive evidence was discovered which tended to indicate that the two groups are unconformable, the facts are believed to warrant the belief that the sandstones form a single essentially conformable series. What has

heretofore been called the "western sandstone" (here called the Bayfield group) is united by Thwaites with the underlying Upper Keweenawan arkose sediments (here called the Oronto group) as one continuous formation. The results of this work show that the contact of the upper, or Bayfield, group with the Middle Keweenawan traps is a fault. At this contact there is some evidence of unconformity, but the author, following Van Hise and Leith, regards it as certain that the folding, faulting, and erosion went on during the deposition of the entire sandstone series, and that the upper beds therefore overlapped with slight unconformity upon the older strata of the same series. The difference in the degree of folding of the two groups of sandstone is correlated with this fact. Both groups were probably deposited subaerially in a basin formed by the bowing of the earlier Keweenawan rocks. They comprise an enormous thickness of sediments, perhaps amounting to as much as 25,000 feet measured in the ordinary way. But the thick series was laid down while deformation of the region was in progress and thus embraces beds which overlap and shingle one another, greatly lessening the total bulk of the formation.

The results of this study, while throwing much light upon the stratigraphic relations in the Lake Superior district, do not in any way determine the relation of the Keweenawan to the Cambrian of the Mississippi Valley. But the fact that the Bayfield group was involved in the profound deformation of the Keweenawan period contrasts it sharply with the slightly disturbed strata of the recognized Cambrian of Wisconsin and Minnesota. The Bayfield group as here interpreted seems, therefore, to be more closely allied to the Keweenawan than to the Cambrian. But this may be apparent rather than actual. For it is not unreasonable to suppose, as Van Hise and Leith have suggested in their *Lake Superior Monograph*, that subaerial sedimentation may have continued within this inland basin nearly or quite up to the time when the advancing Upper Cambrian sea entered the Lake Superior basin. It may therefore be that these sandstones deposited on land may bridge the gap between Proterozoic and Paleozoic. But until the relation of these sandstones to the fossiliferous beds of proven Cambrian age can be determined, the question of the age of the red sandstones still remains a debatable one. It is greatly to be hoped that the author will be able to carry the investigation farther in the endeavor to connect the Lake Superior sandstones with the fossiliferous St. Croix beds lying to the southwest in Minnesota, or with the Cambrian beds lying to the eastward in Michigan.

R. T. C.

The Sub-Oceanic Physiography of the North Atlantic Ocean. By PROFESSOR EDWARD HULL. In atlas form, folio size; 11 charts. London: Edward Stanford, 1912.

This, in the opinion of the reviewer, is one of the most important works on oceanography that has ever appeared. It is handsomely published and on such a scale as to show satisfactorily the evidence of the submarine features from the numerous soundings. While many writers have investigated the form and depth of the ocean floor, the nature of the valleys and canyons which cross the continental platform extending beneath the ocean have generally been passed almost unobserved. These omissions on the eastern side of the Atlantic have been filled to a large extent by Professor Hull's investigations, now brought together out of the scientific journals where they appeared, in such a way as to take on their most convincing form. On the European side, Hull shows how the British platform, extending toward Iceland, is deeply indented by the great Spencerian Gulf; how it is crossed by the Irish Sea river, the English Channel river, and other valleys; how the edge of the platform is indented by short embayments such as characterize the border of plateaus high above tide. Similar features appear about the Bay of Biscay where the canyon of Adour is one of the most remarkable. Like features appear also in the canyon of the Tagus and in others that lie off Portugal. Like phenomena are also shown to occur in the Mediterranean. Such also is the great submarine canyon of the Congo to which a separate chapter is devoted.

The analogous features on the western border of the Atlantic and in the West Indies had previously been investigated by Spencer, who contributes a chapter to Hull's book.

Concerning Spencer's original work Professor Hull speaks in very laudatory terms but in this generous tribute to a coworker it should be recognized that this line of inquiry was far from fully deployed until Hull had directed attention to the significant features that occur on the eastern side of the Atlantic and Nansen had published his Memoir touching upon the same subject. Spencer's chapter in Hull's monograph describes some of the most important features of the American side of the Atlantic in narrative form and this supplements and renders more comprehensive the work of Hull in Europe.

Thus the leading data relative to the submerged river-like valleys and canyons on the border of the continents facing the North Atlantic are assembled in convenient and instructive form.

J. W. SPENCER

Practical Field Geology. By J. H. FARRELL. New York: McGraw-Hill Book Co., 1912. Pp. 273+xi; figs. 66; tables 4. $2.50.

The title of this handbook is in a sense misleading. Instead of being an exposition of approved methods with practical pointers and helpful short cuts for the use of the general geologist in the field, the word practical is here construed as synonymous with mining, and the book is avowedly limited to a treatment of the field methods employed by mining geologists, engineers, and prospectors. Within the field of mining its scope is further limited by the omission of coal and iron from consideration. And in value coal and iron are the greatest of our mining products.

But within its own chosen field the book can be recommended as a useful guide. In the first five chapters the methods of topographic mapping and some of the simpler phases and problems of geologic mapping are well described and presented so as to be available for use by those who have not had the advantages of elaborate training along geological lines. Then come very readable and instructive chapters on the interpretation of geologic data, general suggestions for geologic work, geological measurements, application of descriptive geometry to mining problems, application of geological theory, rock classification, geological prospecting, and prospecting by drilling. These discussions should be of value to those entering the field of economic geology without specialized training in that line.

Following the main part of the book is a guide to the "sight recognition" of 120 common or important minerals, by A. J. Moses.

R. T. C.

The Coal Fields of King County. By GEORGE WATKINS EVANS. Bull. No. 3, Washington Geol. Surv. Pp. 247; figs. 59; pls. 23. Olympia, 1912.

Washington is the only state on the Pacific coast which produces coal in any quantity and most of this comes from the region between Puget Sound and the main range of the Cascades, principally from King and Pierce counties. The coal beds of these two counties belong to the Puget formation whose age has been determined as Eocene. In character this coal ranges from lignitic bituminous in the less disturbed western part of King County to a bituminous coal in the eastern portion where crustal movements and igneous activity have been more severe. It is a coal that is suited to a great many purposes, though it is not the

equal of some of the high-grade eastern coals, or some of the coal from the Alaskan fields. The careful studies which have been devoted to the geological and commercial problems connected with the King County coal fields are well set forth in this bulletin.

R. T. C.

Geology and Ore-Deposits of the Nizina District, Alaska. By FRED W. MOFFIT and STEPHEN R. CAPPS. Bull. 448, U.S. Geol. Survey. Pp. 108; pls. 12; figs. 11. Washington, D.C., 1912.

The Nizina district is located about eighty miles north of Behring glacier between parallels 61° 12′ and 61° 37′ north latitude and meridians 142° 22′ and 143° west longitude, and embraces about three hundred square miles. The sedimentary rocks are Triassic and Jurassic with some Quaternary deposits and rest upon greenstone of probable Triassic age. Deformation and erosion followed Triassic sedimentation with exposure of the underlying greenstone, after which Jurassic sediments accumulated to a thickness of 7,000 feet. Younger rocks may possibly have been present but if so have been removed. The Jurassic rocks are deformed and cut by great quantities of quartz diorite porphyry in the form of sills and dikes. All the rocks are faulted. Most of the Quaternary deposits are related to glaciation.

Gold is the only metal at present produced on a commercial basis but the copper will be important when means of transporting it to the coast are developed. The gold is in the form of placers some of which are related to glacial deposits though others are not. The copper occurs as chalcocite and bornite with small amounts of native metal in the amygdaloidal form. The origin of the copper deposits is discussed briefly, with full recognition of the speculative nature of the chemical reactions.

E. A. S.

The Late Glacial and Post-glacial Uplift of the Michigan Basins. Earthquakes in Michigan. By WILLIAM HERBERT HOBBS. Mich. Geol. and Biol. Surv. Pub. 5, Geol. Series 3. Pp. 87; pls. 4; figs. 53.

This is a bulletin which is largely intended to present a phase of geology in a popular way. The author has preceded his discussion of the uplift by a series of notes and drawings of various features that are useful in interpreting the history of the basins. These include illustrations of present sinking and rising shore lines, sea cliffs, wave-built terraces,

abandoned shores, bars, barriers, etc. The departure of the shore line from horizontality is used for the determination of the amount and direction of tilting.

Reference is made to the prophecy of Gilbert as to the future reversal of the drainage of the St. Lawrence basin but a modification is offered, based upon a study of the hinge lines crossing Lake St. Clair, and upon the fact that no submergence has been noted near Chicago. The author believes that there are no processes now in operation which tend to reverse the St. Lawrence drainage and so bring about the predicted future discharge through the former Chicago outlet.

The hinge lines of tilting have migrated northeastward following glacial retreat, so that the present southernmost line lies north of the Port Huron isobase.

The pamphlet concerning Michigan earthquakes is largely historical.

E. A. S.

Journal of the Washington Academy of Sciences. Vol. II, January–June, 1912. Washington, D.C.

The separate numbers contain advance notices and brief summaries of articles to appear in various scientific periodicals. These are of marked clearness and value because they are, for the most part, prepared by the authors themselves. Occasional complete papers are contributed, notably those by Nutting on the ether, and by Brooks on applied geology. The proceedings of the local scientific societies are also reported and the journal affords a good medium of thought-exchange for the large number of progressive scientists that are centered in the capitol city.

E. A. S.

Triassic Fishes of Connecticut. By CHARLES R. EASTMAN. Bull. 18. State Geol. and Nat. Hist. Survey. Pp. 75; pl. 11; figs. 8.

Paleontology should be regarded as an extension of human history and one of its great contributions is the expansion of the principles that seem to govern organic and social evolution.

The view that Triassic deposits of eastern America were formed in tidal estuaries that were brackish or nearly fresh is replaced by the conception that they include torrential fans from neighboring mountains, fluvial and lacustrine deposits on the lowlands, and probably some

estuarine sediments. Accumulations of wind-blown material no doubt took place on the land. Judgment based on paleobotanical evidence has previously correlated the Triassic system with the European Keuper, but the occurrence of *Ptycholepis Marshi* (Newberry) in accompaniment with *Semionotus*, *Catopterus*, and the Crossopterygian genus *Diplurus* has led to the assignment of the Newark to a horizon that corresponds in a general way to the interval between the Muschelkalk and the Lower Keuper of European marine Trias. The author has discussed the significance of the fauna but has not recognized the generally accepted classification of the geological time-scale.

E. A. S.

Geology and Ore Deposits of the Index Mining District. By CHARLES E. WEAVER. Bull. 7, Wash. State Geol. Survey. Pp. 93; pls. 7.

A brief discussion of the physical history of the region is given with the general geology. The oldest rocks are provisionally assigned to the Carboniferous, but, like most of the older rocks of the region, they are highly metamorphosed. Much of the geological record is obscure. Some good mine maps add to the clearness of the report.

E. A. S.

Geology and Ore Deposits of the Meyers Mining District, and Geology and Ore Deposits of the Oroville-Nighthawk Mining District. By JOSEPH B. UMPLEBY. Bull. 5, Wash. State Geol. Survey. Pp. 107; figs. 5; pls. 3.

A reconnaissance report on the general geology and ore deposits of these areas; brief description of the various mining properties are included; unfortunately no index map accompanies the bulletin.

E. A. S.

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THE SIGNIFICANCE OF RECENT DEVELOPMENTS IN THE PRE-CAMBRIAN STRATIGRAPHY OF THE LAKE SUPERIOR–LAKE HURON REGION

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INTRODUCTION

The geological investigations carried on during the last decade in the northern parts of the Canadian provinces of Ontario and Quebec have added much to our knowledge of the pre-Cambrian terranes of that region, notably so in the Lake Timiskaming district, where the discovery of the silver-bearing veins at Cobalt and of the auriferous quartz lodes at Porcupine has led to extended exploration in the adjoining country. And it is now generally accepted that the pre-Cambrian rocks of northwestern Quebec and northeastern Ontario fall naturally into two strikingly different divisions, separated by a most profound (pre-Huronian) erosion interval. It is also possible, as will be shown in the following pages, that the ancient peneplain or paleoplain formed during this interval, was continuous with the pre-Animikie or Eparchaean[1] erosion plane which occurs in the region north and west of Lake Superior, and that the so-called Lower or Lower-Middle Huronian sediments found in the same locality are in reality a part of the basement complex and pre-Huronian in age.

[1] A. C. Lawson, *Bull. Univ. of Cal.*, III, 50–62.

PRINCIPLES OF PRE-CAMBRIAN CORRELATION

Since pre-Cambrian rocks are generally unfossiliferous, their correlation must be based on either their lithological similarity, their similar stratigraphical relations or their similarity of structure. The criteria of pre-Cambrian correlation may thus be enumerated as follows: (1) stratigraphical relations; (2) lithological character; (3) degree of folding and metamorphism; (4) relationship to igneous intrusions. These will accordingly be used as the basis of the correlations suggested in the following pages.

LAKE HURON–LAKE TIMISKAMING–LAKE MISTASSINI REGION

The earliest stratigraphical investigation of the pre-Cambrian rocks occurring in the Lake Superior–Lake Huron region was that of Logan and Murray on the north shore of Lake Huron, where they found a great series of slightly folded sediments resting unconformably on a basement complex consisting chiefly of granite and gneiss. To the rocks of the first group the name Huronian was given, while the granite and gneiss were correlated with the similar Laurentian granite and gneiss occurring in the vicinity of the Ottawa farther to the eastward. From this classification it is apparent that, theoretically at least, Logan recognized the divisibility of the pre-Cambrian into a Huronian system and an older complex, although both he and his successors in the later reconnaissance work carried on in other districts included greenstones, green schists, and other rocks in the Huronian which are now known to belong to the basement complex.

It was not until about ten years ago, when detailed geological work was begun in the Timiskaming region, that it was found that in this district as on the north shore of Lake Huron a series of slightly disturbed sediments rested in striking erosional and structural unconformity on a basement complex.[1] This complex contained a large proportion of volcanic rocks which were then called Keewatin on the assumption that they were the equivalent of similar rocks occurring in the Lake of the Woods region 500 miles to the westward.[2] In this way it became customary to divide the older complex of the Timiskaming region into two divisions, (1) the

[1] A. E. Barlow, *Ann. Rep. G.S.C.*, XV, 127*a*, 1903.

[2] W. G. Miller, *Ann. Rep., Ont. Bur. of Mines*, Pt. II, 1905.

Keewatin, which included the surface rocks, composed largely of volcanic flows, and (2) the Laurentian, consisting largely of plutonic granite and gneiss. During the last few years, however, has it been found that the so-called Keewatin complex includes a much larger proportion of sedimentary rocks—conglomerate, arkose, greywacke, slate, etc.—than was formerly supposed, and to these various local names—Pontiac schist,[1] Fabre Series,[2] Timiskaming Series,[3] Sudbury Series, etc.—have been given. These rocks have been found in almost every area where detailed geological work has been carried on. They occur in the Sudbury district, in the vicinity of Lake Timagami, in the Larder Lake district, in the Cobalt region, in the Porcupine district and in numerous localities in northwestern Quebec. In the last-mentioned region a belt of fine-grained, rusty mica schist, which contains squeezed pebbles of granite and greenstone, has been traced continuously for 100 miles by J. A. Bancroft and the writer. Throughout all this distance the schist is intruded by dikes of granite, aplite, and pegmatite, showing conclusively that it is older than at least part of the Laurentian gneissic complex. In defining the various series to which these rocks have been referred, it has been assumed in most cases, (1) that they belong to the Huronian, and (2) that they are younger than all the volcanics of the basement complex.

Both of these assumptions are probably unwarranted. In objection to the use of the name Huronian for the sediments occurring in the volcanic complex, it might be pointed out that they occur throughout an area of many thousand square miles, and everywhere possess characteristics which are distinctly at variance with those of the typical Huronian. They form a part of a basement complex which, as shall be shown later, probably lies stratigraphically below the original Huronian. Lithologically they have little in common with the original Huronian, and unlike the Huronian, they are everywhere highly folded, foliated, and intruded by granite batholiths. The second of these assumptions implies that the sedimentary rocks are stratigraphically as well as lithologically separate from the volcanics, a conclusion which is con-

[1] M. E. Wilson, *Sum. Rep. Geo. Surv. Dept. of Mines, Can.*, p. 175, 1909.

[2] R. Harvie, *Geology of a Portion of Fabre Township* (Dept. of Mines, Que.), 1911.

[3] W. G. Miller, *Eng. and Min. Jour.*, XCII, p. 648, 1911.

trary to the facts, for, while the presence of a heterogeneous assortment of pebbles in the conglomerate indicates that a great erosion interval is probably represented, there is evidence, in some localities, that the sediments and volcanic flows are interbedded and consequently, if two series are present, it is evident that volcanic flows occur in both. In many localities either because of the highly deformed condition of the rocks, or because of the paucity of exposures, or because of the lithological similarity of the volcanic flows, it is not possible to separate these various rocks into stratigraphical divisions. For these reasons it seems necessary at present to class them together into one group regardless of possible differences in age, making merely such subdivisions as are convenient for the purpose of lithological description. In accordance with the foregoing conclusion the writer has adopted the term Abitibi group to include all the surface rocks, i.e., the sediments and volcanic flows, of the older complex occurring in the Timiskaming region. Since the surface rocks are placed in the Abitibi group, the plutonic granite and gneiss must naturally be referred to the Laurentian. But it is important to note that the Laurentian according to this definition, most probably includes granitic rocks of at least two periods of intrusion, as shown by the presence of granite pebbles in conglomerate which is itself intruded by granite.

The flat-lying sediments which rest on the base-leveled surface of the basement complex in the Timiskaming region, when first recognized as distinct from the underlying volcanics, were called Lower and Middle Huronian,[1] but as there was some doubt as to which particular division of the Huronian they should really be referred, they are now generally known as the Cobalt series.[2] They outcrop throughout a region extending from the Abitibi district in Quebec to the Sudbury district in Ontario, and occupy an area of not less than twenty thousand square miles. Throughout all this area they rest on a remarkably uniform erosion surface, which might be described as a fossil peneplain.

In the Chibougamau district near Lake Mistassini, 200 miles to the northeast of the Timiskaming region, there is a series of slightly disturbed sediments which resembles the Cobalt series

[1] *Ann. Rep., Ont. Bur. of Mines*, Pt. II, 1905.

[2] W. G. Miller, *Eng. and Min. Jour.*, XCIII, 643, 1911.

both in its lithological character and in the stratigraphical succession of its members, and like the Cobalt series rests on the trunkated surface of a basement complex.[1] Throughout the intervening distance between Lake Timiskaming and Lake Chibougamau, no outcrops of the Cobalt series have been described, but the Abitibi group and the Laurentian are typically developed throughout the whole interval. From these facts it may be concluded that the pre-Cobalt series erosion plane, the Abitibi group and the Laurentian extend eastward to the Chibougamau district.

From the evidence already cited it might be inferred that the pre-Cobalt series erosion plane is also the equivalent of that which underlies the original Huronian rocks on the north shore of Lake Huron, but since a large part of the conclusions of this paper are based on the correlation of these two planes, it is important that the evidence be stated in full. In support of their correlation it might first be pointed out that the Cobalt series and the two original Huronian series are structurally and lithologically very similar, even to the presence of a sea-green quartzite containing pebbles of jasper and quartz. It is true that until recently, it was thought that the limestone was absent in the Cobalt series, but as that series is traced southward it changes somewhat in character, and limestone beds have been found to be present in the district north-east of Sudbury.[2] Not only are the original Huronian rocks similar to the Cobalt series, but there is no other series in the Timiskaming region which resembles them either in lithological character, structure, or relationship to batholithic intrusions. The basement complex which underlies the original Huronian rocks has not been studied in detail, but like that beneath the Cobalt series, it consists in the main of metamorphosed volcanic flows intruded by granite and gneiss. Thus in both districts an older complex occurs which is separated from the overlying slightly disturbed sediments by erosion planes, which would coalesce if projected across the interval which intervenes between the known occurrences of the Cobalt series and the original Huronian.

From the foregoing discussion it follows that throughout the

[1] *Rep. on the Geol. of the Chibougamau Region* (Dept. of Mines, Que.), pp. 134–38, 1911.

[2] W. H. Collins, *Sum. Rep. Geo. Surv. Dept. of Mines, Can.*, 1913.

Lake Huron–Lake Timiskaming–Lake Mistassini region, pre-Cambrian sedimentary rocks occur here and there, which were laid down upon the surface of a basement complex. This of course does not make it necessary that the original Huronian rocks, the Cobalt series and the rocks described as Huronian in the Chibougamau district, are wholly contemporaneous. In fact this is scarcely probable since there are two series present[1] in the original Huronian group of rocks and, as far as known, only one elsewhere. Nevertheless it is evident that all of these younger sediments were derived from similar sources, that they originated under somewhat similar conditions, that their history since their deposition has been similar, and that the floor upon which they were deposited was the same.

THE LAKE SUPERIOR REGION

Having shown that an early pre-Cambrian paleoplain extends throughout such a wide area of country in northwestern Quebec and northeastern Ontario, two questions now present themselves: (1) does this pre-Huronian erosion plane extend throughout the Lake Superior region, and (2) what rocks in that area correspond to the basement complex of the Lake Huron–Lake Timiskaming–Lake Mistassini region?

From the geological reports which have been published with regard to various districts in northern Ontario and the adjacent portions of United States to the west of Lake Superior, it is known that throughout the wide area of country which extends from the Timiskaming region to the Vermilion district in Minnesota, there is a basal (pre-Animikie) complex composed in part of volcanic rocks and in part of granite and gneiss, and in almost every locality where detailed work has been carried on—on the east shore of Lake Superior near Batchawana bay,[2] in the Michipacoten district,[3] near Heron bay on the northeast shore of Lake Superior,[4] in the Nipigon district,[5] in the vicinity of Port Arthur,[6] in the region

[1] According to C. R. Van Hise, *Bull. Geo. Soc. Am.*, p. 5, 1908.

[2] *Ann. Rep. Ont. Bur. of Mines*, p. 127, 1892.

[3] *Ibid.*, pp. 152–85, 1902.

[4] *Ibid.*, p. 127, 1892.

[5] *Ibid.*, 1908, 1909; *National Transcontinental Railway between Lake Nipigon and Sturgeon Lake* (Geol. Surv. Dept. of Mines, Can.), 1908; *Geology of the Nipigon Basin*, Memoir No. 1 (Geol. Surv. Dept. of Mines, Can.), 1910.

[6] *Ann. Rep. Ont. Bur. of Mines*, pp. 254–60, 1905.

between Lake Savant and Lost Lake,[1] in the Lake of the Woods and Rainy Lake districts,[2] in the Vermilion district,[3] and at Steep Rock Lake,[4] it has been found that highly metamorphosed conglomerates, slates and schists of sedimentary origin occur in association with the volcanics and, as in the pre-Cobalt series complex of the Timiskaming region, the conglomerate although intruded by granite contains granite pebbles. But in only two localities—the Vermilion district and Steep Rock Lake—has the conglomerate been found resting unconformably on the surface of the older granite from which its pebbles were derived.

Here and there this basement complex is overlain by two series of almost flat-lying sediments, the older of which is known as Animikie and the younger as Keweenawan. In some places, as on the shore of Thunder Bay, both series are present; but in others the Animikie occurs alone, or the Animikie is absent and the Keweenawan rests directly on the surface of the complex.

The names which have been applied to the various formations composing the (pre-Animikie) complex found in the region north and west of Lake Superior, have varied in different localities and at different times. For many years following the work of Logan and Murray on the north shore of Lake Huron, the geologists who investigated these pre-Cambrian terranes, with but one notable exception, called the granite and gneiss Laurentian and the volcanic complex Huronian. But A. C. Lawson who reported on the geology of the Lake of the Woods and Rainy Lake regions for the Canadian Geological Survey, departed from the general custom and adopted a local nomenclature. According to Lawson's classification the granite and gneiss were Laurentian, but the volcanics and sediments were grouped into an Ontarian system which had two divisions, the Coutchiching series, largely composed of sedimentary mica schist and the Keewatin, consisting for the most part of volcanics. In the Vermilion district of Minnesota, where much detailed geological work has been carried on since Lawson's reports

[1] *National Transcontinental Railway between Lake Nipigon and Clay Lake* (Geol. Surv. Dept. of Mines, Can.), 1909; *Ann. Rep. Ont. Bur. of Mines*, 1910.

[2] *Ann. Rep. G.S.C.*, I, Part CC, 1885; *ibid.*, III, Part F, 1887–88.

[3] *U.S.G.S. Mon.*, XLV, 1903; *ibid.*, Vol. LII, 1911.

[4] *Memoir No. 28* (G.S. Dept. of Mines, Can.), 1912.

were published, the volcanic rocks of the complex have been classed as Keewatin in accordance with Lawson's nomenclature, but the name Laurentian has been limited to the older granite which lies unconformably beneath the Ogiskie conglomerate and Knife Lake slates, while these sediments, along with the younger granite which intrudes them, have been designated Lower or Lower-Middle Huronian. The scheme of classification worked out in the Vermilion region is essentially the same as that indorsed by the International Committee in their report on the pre-Cambrian nomenclature of the Lake Superior region[1] and has been generally adopted, as far as practicable, by Canadian geologists engaged in geological work in the pre-Cambrian regions of northern Ontario and Quebec.

But in applying this classification in the Lake Huron–Lake Timiskaming region, serious difficulties have been encountered, for the rocks known as Lower-Middle Huronian in the region north of Lake Superior are similar in every respect to the younger (Timiskaming, etc.) series occurring in the pre-Cobalt series complex, whereas the name Lower-Middle Huronian implies that they are approximately equivalent in age to the Cobalt series and the original Huronian, which they resemble in no particular whatever. While it might be objected that the Lower-Middle Huronian rocks of the region north of Lake Superior are too far distant from the rocks composing the Timiskaming series for their correlation, yet, if the rocks occurring in these two regions are to be correlated at all, then the Lower-Middle Huronian must certainly be correlated with the pre-Huronian Timiskaming series, rather than with the Cobalt series or the original Huronian. At any rate, it is at least probable, from the remarkable lithological and structural similarity of the basal pre-Cambrian rocks occurring throughout the whole region from Lake Superior to Lake Timiskaming, and the evidence of the presence of an erosion interval in the pre-Cobalt series complex, similar to that beneath the Ogiskie conglomerate in the Vermilion region, that the rocks which underlie the Cobalt series in the Timiskaming region are the same as those beneath the Animikie series in the region north and west of Lake Superior and that the pre-Huronian paleoplain occurring in the Lake Huron–Lake

[1] *Jour. of Geol.*, XIII, 89–104, 1905.

Timiskaming region was originally continuous with the pre-Animikie or Eparchaean erosion plane. It also follows from this conclusion that the name Lower or Lower-Middle Huronian for any series of rocks in the basement complex occurring to the north and west of Lake Superior is inapplicable; nor does the limitation of the name Laurentian to the older granite in the Vermilion region seem advisable, for this usage is not only contrary to the original definition of the term, but also contrary to the requirements of our nomenclature, since in many localities it is impossible to state whether a particular granite or gneiss belongs to the younger or older of the granitic rocks recognized to be present in the pre-Cambrian basal complex.

The conclusion that the rocks classed as Lower or Lower-Middle Huronian in the region north of Lake Superior are probably pre-Huronian in age was reached from two premises: (1) that the same series of rocks is present in the complex which underlies the Cobalt series, and (2) that the pre-Cobalt series complex also underlies the original Huronian rocks on the north shore of Lake Huron. By making a direct comparison of the Lower-Middle Huronian rocks occurring to the north of Lake Superior with those occurring to the south of the lake, this correlation may be tested in another way. In the region south of Lake Superior, as in the other pre-Cambrian areas, there is a basement complex composed of greenstone and green schist intruded by batholiths of granite and gneiss, but in that locality the complex is overlain by a succession of four rock series. These, named in ascending order, are known as Lower Huronian, Middle Huronian, Upper Huronian, and Keweenawan respectively. The Lower and Middle Huronian are believed to be the equivalent of the original Huronian on the north shore of Lake Huron, while the Upper Huronian is correlated with the Animikie series of the north shore of Lake Superior. The Keweenawan series, as the name implies, is also believed to correspond to the series of the same name on the north shore of Lake Superior. These correlations have been generally accepted[1] and are almost wholly in accord with the criteria of pre-Cambrian correlation, so that for the purpose of this discussion they may be taken as repre-

[1] R. D. Irving, *Am. Jour. Sci.*, XXXIV, 204, 1887.

senting the facts. And since there is a series of rocks in the older complex north of Lake Superior classed as Lower-Middle Huronian, it has evidently been assumed that it is the equivalent of the Lower and Middle Huronian occurring to the south of Lake Superior. Accordingly, by comparing the Huronians of the two regions, we can ascertain on what facts their correlation has been based.

1. The Huronian rocks of the southern area are largely quartzites, limestones, dolomites, and slates, while those of the northern area consist for the most part of conglomerate slate and mica schist. Their correlation has therefore not been based on the similarity of their lithological character.

2. The Huronian of the north is intruded by batholiths of granite and gneiss; that of the south is not so intruded. It is also evident therefore that their correlation cannot be attributed to any similarity in their relationships to igneous intrusions.

3. The northern Huronian has not only been more highly folded and deformed than the southern, but the deformation occurred at a much earlier period in the north than in the south, for the Animikie rocks of the north are not only almost flat-lying, but they rest on a peneplained surface, so that the deformation in the underlying complex was complete long before the Animikie sediments were laid down. To the south of Lake Superior, on the other hand, the Animikie and Keweenawan rocks are highly folded, and hence, if the Animikie and Keweenawan deformation were eliminated throughout the whole Lake Superior region, the southern Huronian would be but slightly disturbed, whereas that of the north would be just as much folded and deformed as at present. It is again apparent therefore, that the northern Lower-Middle Huronian has not been correlated with that of the south, on the grounds that both have been folded and deformed to the same degree or at the same time.

4. The Huronian to the south of Lake Superior like that to the north, rests unconformably on the surface of a complex composed of greenstone, greenschist and iron formation (Keewatin) intruded by granite and gneiss, so that the stratigraphical relations of the Huronians in both localities are apparently the same; and it was evidently upon this fact that their correlation was based, but in

considering the stratigraphical relations of greater importance than all the other criteria combined, the geologists who made the correlation ignored the possibility of overlap.

The geological investigations carried on throughout the region north of Lake Superior have shown that the rocks classed as Lower-Middle Huronian occur here and there throughout the basal complex as trunkated synclinal remnants, and that relatively their areal extent is exceedingly small; and since the total area of the rocks which have been differentiated as Keewatin in the region south of Lake Superior is only 60 square miles in extent,[1] it is possible that the stratigraphical relations observed are due to the fact that one of these synclinal remnants does not happen to occur in this limited area. If this were the case, then the pre-Huronian complex to the south of Lake Superior and the pre-Animikie complex to the north of the lake would be equivalent, although the stratigraphical relations of the Huronian to the south and Huronian to the north would be apparently the same. Consequently, although the stratigraphical relations of the so-called Lower-Middle Huronian of the Vermilion district are apparently similar to those of the Lower and Middle Huronian to the south of Lake Superior, yet from the consideration of the other facts—that the two groups of rocks are lithologically unlike, that those of the north are intruded by batholiths of granite and gneiss while those of the south are not so intruded, and that the deformation and folding in the south occurred long after that in the north—it must be concluded that the evidence in favor of their correlation is not sufficiently conclusive to preclude the possibility of an alternative hypothesis.

CONCLUSION

The evidence and the conclusions inferred from the evidence as stated in the preceding pages, may be summarized briefly as follows: (1) The paleoplains which underlie the original Huronian rocks on the north shore of Lake Huron and the Cobalt series in the Timiskaming region were originally continuous. (2) The complex which underlies the Cobalt series in the Timiskaming region and that which underlies the Animikie series in the region

[1] *U.S.G.S. Mon.*, Vol. LII, Plate I, 1912.

north of Lake Superior are the same. (3) From (1) and (2) it is inferred that the pre-Huronian erosion plane was also originally continuous with the pre-Animikie or Eparchaean erosion plane, and that the rocks classed as Lower-Middle Huronian in the region north of Lake Superior are therefore a part of the basement complex and in reality pre-Huronian in age. (4) If the rocks classed as Lower and Middle Huronian in the region south of Lake Superior have been correctly correlated with the original Huronian, then these series must also be younger than the Lower-Middle Huronian of the region north of Lake Superior; (5) A direct comparison of the Lower-Middle Huronian of the region north of Lake Superior with the Lower and Middle Huronian occurring to the south of Lake Superior shows that the correlation of these series is based on evidence from which an alternative inference conforming to the conclusion cited in (3) may be drawn.

With the progress of geological investigation in the pre-Cambrian terranes of the Canadian oldland, new facts are constantly being added to our knowledge of their stratigraphy, and from the evidence now available it can be reasonably inferred that the pre-Cambrian rocks throughout the whole of the Lake Superior region and eastward through northern Ontario and western Quebec, fall naturally into two great divisions, an older complex and a group of younger rocks, which differ from the complex in that they generally contain a much larger proportion of sediments, are generally much less highly folded and metamorphosed, and as far as geological investigation has shown, are nowhere intruded by batholiths of granite or gneiss. This younger group of rocks includes (1) the Cobalt series in the Timiskaming region, (2) the Animikie and Keweenawan series in the region north of Lake Superior, (3) the original Huronian series on the north shore of Lake Huron, and (4) the rocks known as Lower Huronian, Middle Huronian, Upper Huronian and Keweenawan in the region south of Lake Superior. This conception of the stratigraphical relationships of these various younger pre-Cambrian series involves no unusual phenomena, for just as in later geological periods Cretaceous, Silurian, and other sediments of different ages were deposited on the surface of the same basal complex, so in Huronian

time, the Animikie series might be laid down on the same erosion surface on the north shore of Lake Superior, as the Huronian on the south. If the Lower and Middle Huronian series are not present in the region north of Lake Superior, it must simply be inferred that they were never deposited in that region, or, if deposited, they were eroded away before the Animikie sediments were laid down, and that the geological time represented by the Eparchaean interval in the region north of Lake Superior is represented in the region south of the lake, by three erosion intervals and two series of sediments.

The rocks comprising the basement complex which everywhere underlies the younger pre-Cambrian series, have suffered so many vicissitudes that although there is evidence, in many localities, that two series of surface rocks and granitic batholiths of two periods of intrusion are present, yet it is not possible in many places to separate the rocks stratigraphically from one another. For this reason the only *regional* classification practicable *at present*, is to divide the complex into two divisions according as to whether they belong to the plutonic or surface types. For the plutonic rocks the name Laurentian has been generally used, and while this name, according to the original conception of Logan, might be more properly referred to the whole basement complex, it has since been referred to the plutonic types so constantly, both by Logan and by his successors, that it seems best to use it with that significance. For the surface rocks of the complex, the writer has used the name Abitibi group in the Timiskaming region, but this probably corresponds to the Ontario system into which Lawson grouped the Keewatin and Coutchiching series occurring in the Lake of the Woods and Rainy Lake regions. The subdivisions of the basement complex (Archaean) according to this classification would thus be as follows:

HURONIAN

PRE-HURONIAN PALEOPLAIN

Basement Complex	Laurentian	Younger Laurentian granite and gneiss.
		Older Laurentian granite and gneiss.
	Ontarian or Abitibi group	Composed of at least two series, to be given local names where subdivision is possible.

The regional correlation of pre-Cambrian rocks from the nature of the evidence upon which it is based must always be to a degree hypothetical, but so long as it is logically inferred from a reasonable number of facts and its hypothetical character is kept in mind by geologists, it serves a useful purpose in the progress of our science. In the report of the Special Committee on the Lake Superior region, certain sedimentary rocks included in the basement complex to the north of Lake Superior were called Huronian, and thus tacitly correlated with the Huronian rocks occurring in the region south of Lake Superior and on the north shore of Lake Huron. The purpose of the present paper has been to point out that from a careful consideration of the facts now at hand, it must be concluded that the evidence on the whole is equally in favor of an alternative hypothesis, that these ancient sediments are a part of the older complex which underlies the Huronian, and are pre-Huronian in age.

THE ORDER OF CRYSTALLIZATION IN IGNEOUS ROCKS

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A recent paper in this journal by Mr. Victor Ziegler[1] takes the form of a criticism of a paper by Bowen on the order of crystallization in igneous rocks.

Ziegler does not question the statement of Bowen that "the observation of all the relations of outline of a number of minerals in a section of a holocrystalline granular rock leads to a safe conclusion only as to the order in which the minerals have ceased to crystallize." The fact that there is agreement on this point is worth noting.

Ziegler does, however, believe that this order of cessation of crystallization must be also the order of beginning of crystallization. He says, "the order of cessation of crystallization gives a definite clue to the order of beginning of crystallization," although he himself has discussed the crystallization of three-component metal systems in which the final crystallization always consists in the simultaneous formation of three solid phases (simultaneous cessation of crystallization), whatever difference there may be in the order of beginning of crystallization which varies with the relative proportions. Clearly in those systems the cessation of crystallization gives no clue to the beginning.

Bowen in the original paper clearly recognized that if the crystallization of a rock magma is analogous to that of the simple chemical systems that have been studied, the final crystallization should consist in the formation of a number of solid phases (polycomponent eutectic) and that there would be no *order* of cessation of crystallization. It was suggested that the complications which follow from the prevalence of solid solutions among the components of rock magmas might, however, give a result which need not be analogous

[1] *Jour. Geol.*, XXI, 1913, p. 181.

to simple systems. Ziegler discusses two three-component systems in which there is no solid solution and points out that "there is no recurrence of the substance first crystallized in either case. If substances are capable of forming solid solutions they do not affect the above in any way." Yet Vogt,[1] following Schreinemakers has shown beyond doubt that, even in relatively simple systems, solid solution may bring about precisely the result denied it by Ziegler, viz. recurrent crystallization.

In many respects it is entirely unsafe to fall back on analogy with simple systems. The average igneous rock is far from a simple system, neither was it formed under simple conditions. In the finally crystallized product important quantities of borates, fluorides, chlorides, water, CO_2, etc., are not represented. The early portion of the crystallization of a rock magma (the beginning of crystallization) is undoubtedly due chiefly to the cooling-down of the magma, whereas the addition of the final layers to the crystals (cessation of crystallization) may be, *in part*, due to a process which approaches an evaporation during which the above volatile substances are removed. The complications are such that it is entirely unsafe to extrapolate from simple systems investigated under simple conditions.

For this reason Bowen, in the original paper, avoided theoretical discussion, since it must necessarily be on the basis of such extrapolation, and turned to the evidence of the rocks themselves. Thus, certain conclusions were arrived at concerning the order of beginning of crystallization based on the consideration of volcanic rocks as the quenched equivalents of plutonic rocks. Ziegler doubts whether this method is justifiable and points out that the difference of conditions under which volcanic and plutonic rocks crystallize, taking the specific cases of granite and rhyolite, might, theoretically, bring about a different order of crystallization. Certainly, if theoretical considerations were all the light on the subject available, the question would have to remain in this condition of doubt, but there exists other evidence. In nature, rocks occur which have been formed under every conceivable gradation of conditions intermediate between those characteristic of the

[1] *T.M.P.M.*, XXVII, 141–55.

formation of granite and of rhyolite. The rocks formed under these intermediate conditions confirm the evidence of the rhyolites as to the order of beginning of crystallization as Bowen has pointed out. There is not only no evidence that the difference of conditions brings about a reversal in order of crystallization but there is definite positive evidence that no such drastic change occurs.

In view of the fact that the objections of Ziegler are almost entirely the outcome of theoretical considerations which it is dangerous to extend to such complicated systems, and that the evidence of the rocks themselves, on which Bowen based his conclusions, is not questioned, it does not appear that the objections offered seriously impair the conclusions reached by Bowen.

A knowledge of the order of beginning of crystallization is important for the elucidation of the differentiation of rock magmas. Differentiation is not uncommonly discussed in terms of the assumption that ferromagnesian minerals are minerals of early crystallization whether they are present to the extent of 70 per cent or of only 5 per cent. This assumption is often quite obviously at variance with the evidence of the porphyritic facies of the rock types described, and in such cases leads, of course, to erroneous conclusions.

PSEUDOBRECCIATION IN ORDOVICIAN LIMESTONES IN MANITOBA

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THE ORDOVICIAN IN MANITOBA

The Ordovician in Manitoba, as determined by Dowling,[1] consists of the following series in ascending order: (1) The Winnipeg sandstones, directly overlying the eroded surface of the pre-Cambrian. This division consists of beds of soft, often very white, friable sandstones, about 100 ft. thick, containing only a few fossils. The St. Peter sandstone of Minnesota is similar in petrological aspect, but the absence of true Chazy fossils in the Winnipeg sandstone procludes definite correlation with the St. Peter sandstone. The fossils rather suggest upper beds of the Black River, but this formation is in Minnesota represented by shales. (2) The Lower Mottled limestone, exposed along the west side of Lake Winnipeg, and on some of the islands. This formation is about 70 ft. thick. The character of the limestone is very similar to that to be described in detail as the Upper Mottled limestone. It is mottled buff and greyish white, is highly fossiliferous, and shows what are probably fucoidal tracings on the bedding planes. The upper beds are highly charged with siliceous material. (3) The Cat Head limestone, yellow dolomites, even grained and as a rule fine grained, containing cherty concretions which in many instances exceed a foot in diameter. The beds have been estimated to be 68 ft. thick. The large cephalopods which are so common in the Lower Mottled are wanting in the Cat Head series. (4) The Upper Mottled limestone, exposed at several points on the western shores of the northern extension of Lake Winnipeg; also along the Red River, and at the time of Dowling's work more particularly at East Selkirk. Today the limestone quarries of Tyndall provide very good sections of this limestone. The thick-

[1] Geological Survey of Canada, *Annual Report*, 1900.

ness of the division is about 130 ft. Like the Lower Mottled, this limestone is highly fossiliferous, and is characterized by the presence of fossils of large dimensions: various orthoceratites, *Maclurea manitobensis* and *Receptaculites oweni* are particularly abundant. The mottled character of the stone will be subsequently described in detail. The chief difference that has been noted between this and the Lower Mottled is that frequently the pale-colored areas of the Upper Mottled are chalky in character, and readily soil the fingers, a feature not observed in the Lower Mottled. (5) The Stony Mountain formation, a series of ochreous shales overlaid by massive dolomitized limestones, showing a maximum thickness for the whole series of 110 ft. The beds thin out northward. The shales at the base are highly fossiliferous, and probably represent the Utica shales of the Cincinnati group. The top beds of the Ordovician in Manitoba are overlaid, presumably conformably, by the thin-bedded, dolomited limestone of the Niagara formation, exposed at Stonewall and at the mouth of the Saskatchewan River.

Further detailed work is required before an exact correlation of these beds with the Ordovician of Minnesota, Wisconsin, and Iowa can be given. Pending this, the following alternative correlation is submitted, the latter of which seems with the present evidence the more probable.

Minnesota, Wisconsin, and Iowa		Manitoba	Minnesota, Wisconsin, and Iowa
Maquoketa shale		Stony Mountain form (190 ft.)	Maquoketa shale
	Trenton	Upper Mottled limestone (130 ft.)	Galena dolomite
Galena dolomite	Trenton	Cat Head limestone (70 ft.)	Green shales (Black River)
	Trenton	Lower Mottled limestone (70 ft.)	Plattville limestone
Green shales (Black River)		Winnipeg sandstone (100 ft.)	St. Peter sandstone
Plattville limestone St. Peter sandstone			

THE MOTTLING OF THE LIMESTONE

The quarries at Tyndall furnish good exposures of the Upper Mottled limestone. The following description applies more particularly to what was formerly known as Garson's quarry, now under

the management of the Northwest Quarries Co. Ltd. The surface capping of drift is 8–10 ft. thick, and the bowlders are mainly limestone, very few Archaean granites or gneisses being found. Underlying the drift are thinly and irregularly bedded limestones, 3 ft. thick, mottled in similar fashion to the more massive limestones underneath. Then follow 14 ft. of buff mottled limestone, wrought in ledges 3–6 ft. thick (Fig. 1). This is practically homogeneous,

Fig. 1.—Upper Mottled limestone, Garson's Quarry. Tyndall

though certain horizons show the presence of cephalopods more markedly than others (see Fig. 2). Underneath is a blue mottled limestone, uncovered for 6 ft., the darker patches on the stone showing, even on the weathered surface, a darker blue color than on the buff stone. A bore has recently been sunk in order to determine the quality of the underlying strata, and the manager of the quarry, Mr. Pfeiffer, has kindly supplied the following details. The blue mottled is altogether about 13 ft. thick. Underneath this lies a second horizon of buff mottled stone. The quarry and

bore together expose 97 ft. of stone, the lower 62 ft. of which is buff, and so thinly bedded as to be valueless as a dimension stone. In this is found, at a depth of 51 ft. below the top of the limestone in this exposure, a bed 16 ft. thick which might be described as a very impure limestone, high in argillaceous material.

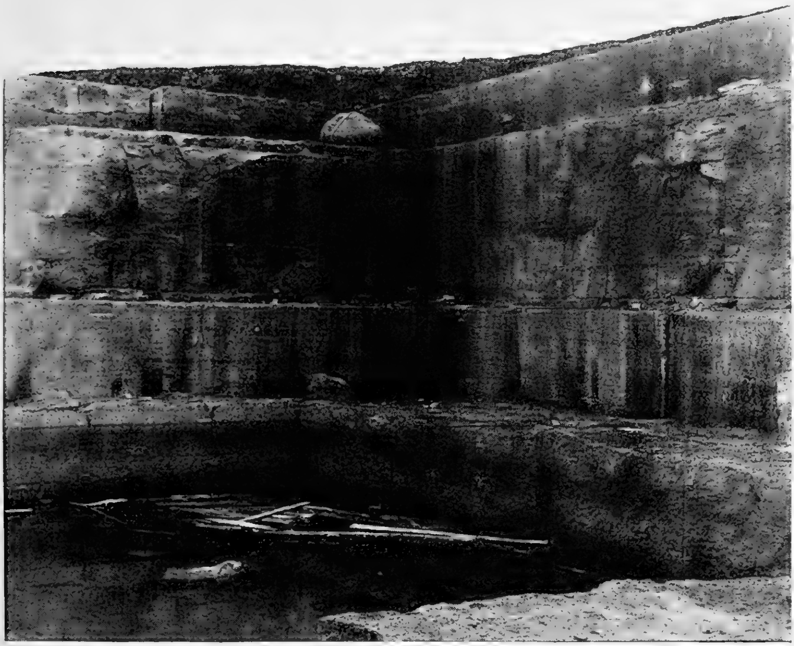

FIG. 2.—Upper Mottled limestone, Henry's Quarry. Tyndall

The rock consists of a light-grey limestone, with patches of darker material scattered through the stone. Though these darker areas are distributed apparently quite irregularly, slabs cut parallel and perpendicular to the bedding planes show that the linear extension of the patches is decidedly along the bedding planes. A comparison of the side of the slab shown in Fig. 3 (cut along the bedding plane) with its end section will be convincing. There is no evidence, on the other hand, of greater development of the darker areas along jointing planes than in any other vertical direc-

tion. The patches, when seen along the bedding planes, have a certain linear development, suggesting branching structures rather than concretionary arrangements. Vertical sections are, however, more commonly roughly circular. The cross-sections are usually not more than $1\frac{1}{2}$ in. in diameter, while along the bedding planes irregularly extended areas 5–6 in. in length are not uncommon.

FIG. 3.—Slab of limestone, cut parallel to bedding plane

What are apparently fucoidal traces have been noted on the bedding planes of both the Upper and Lower Mottled limestone. This may have suggested the only explanation that has been offered as to the origin of the mottling of the stone in this district—that given by Panton:[1]

It [the limestone at East Selkirk] presents a peculiar mottled-like appearance, which adds much to its beauty as an ornamental stone. This strange mixture of brown and white is difficult to account for. In some cases it appears

[1] *Trans. 15 Man. Hist. and Scient. Soc.*, Winnipeg, 1884.

as if the origin might be due to seaweed remains. Often the colored portion approaches the color of yellow ochre, and seems strongly impregnated with iron, while the intervening spaces are more or less colored.

Later work on the Galena and Trenton of Iowa by Leonard[1] has shown that the Galena, which is considered to be a dolomitized phase of the Trenton, is found to grade into the underlying Trenton through strata which possess a somewhat similar mottled appearance to those already described. An analysis showed that the darker areas were dolomitized, while the lighter were unaffected by the magnesia-bearing waters. This was inferred from the chemical analyses for $MgCO_3$ and $CaCO_3$ which were as follows: grey portion, 97.46 per cent $CaCo_3$, 4.31 per cent $MgCO_3$; buff portion, 60.97 per cent $CaCO_3$, 18.28 per cent $MgCO_3$ (*op. cit.*, p. 259). It was also suggested that jointing planes and the spaces between the larger fossils and the surrounding limestone might have served as chambers of passage for the waters which effected the dolomitization. It was observed that although the fossils were not themselves affected, they were frequently surrounded by a dolomitized area.

Under the microscope the difference in structure between the two areas is very apparent (Fig. 5). The darker-colored patches are evenly crystallized, showing sections of rhombohedra of dolomite, set close together, and occasional crystals of hematite passing over into limonite. The color is due to the hematite and, more particularly, the limonite, to which the action of percolating water has imparted a banded structure. Excepting a few large shells, which have not been affected, there are no traces of organic remains in the dolomitized areas (see Fig. 4). The light-colored areas, on the other hand, contain numerous fragments of brachiopod shells, with occasional sections of polyzoa and corals. These are set in a fine-grained calcitic material, strikingly different, even at the margin between the two areas, from the fairly perfectly crystallized dolomite. No hematite or limonite occurs in the lighter material except where occasional local dolomitization has taken place, and there the rhombohedra are always colored by the iron ore. That this is actually a case of pseudobrecciation, and not a

[1] "Geology of Clayton County," *Iowa Geological Survey*, XVI, 259.

FIG. 4.—Polished surface of the limestone

brecciated structure due to the cementation of a dolomite breccia in a calcareous matrix, is evident from the microscopical examina-

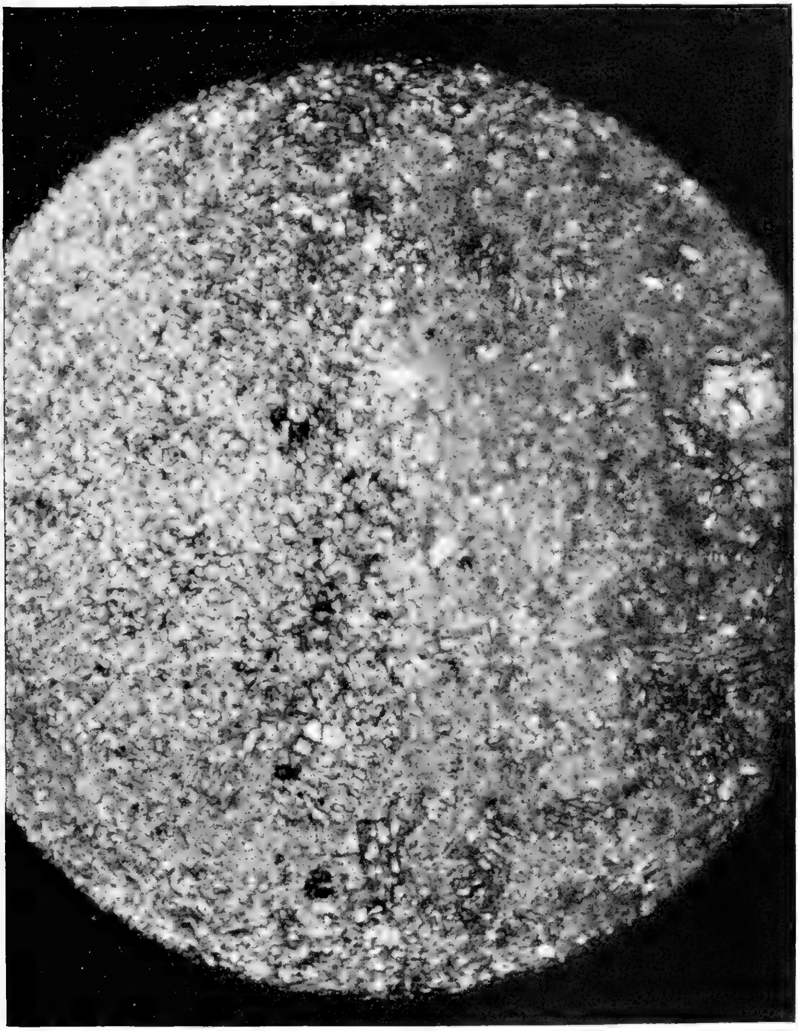

FIG. 5.—Thin section, showing margin between dolomitized (left) and undolomitized (right) limestone. ×31.

tion. In several thin sections there are found at the margins of the dolomitized areas fossils which have been surrounded by a thin

strip of dolomitic material—the dolomitization having ceased when the percolating waters met round the shell. That breccia of such a type could have existed without the fossils becoming detached is hardly possible. A study of the margin of the darker areas leaves no doubt that we are dealing with a secondary dolomitization. Although there is a definite marginal line, it shows so sharp interpenetration of dolomitized and undolomitized material that it could have been caused only by the irregular advance of waters bearing magnesian salts in solution.

Microscopic investigation shows that the hematite, which with the limonite is responsible for the color effect of the darker patches, is found in crystals separate from the dolomite, and at the edges of the dolomite rhombohedra. The dolomite is itself clear and colorless; and the position of the hematite crystals, and their invariable association with dolomitic areas suggest naturally that the hematite was formed by the same agency that gave rise to the dolomitization. From the microscopic evidence alone, the most feasible explanation seemed to be that during the process of dolomitization the ferruginous material, originally present in the form of ferrous carbonate as an isomorphous admixture with the calcitic material, had to a large extent separated out owing to the greater inability of the dolomite to hold the iron isomorphously. Once separated as carbonate, the iron would undergo oxidation much more rapidly than is possible in a mixed crystal where the calcite exercises a controlling influence, retaining the iron in the ferrous state. A chemical analysis should then show—if this theory can be supported—that although the darker areas are richer in magnesia and in ferric iron, and the lighter areas contain practically no magnesia, the total iron is approximately the same in both.

CHEMICAL INVESTIGATION

The two varieties were separated as completely as possible, and subjected to chemical analysis. The calcium was estimated volumetrically, the magnesium gravimetrically. The total iron is given here as Fe_2O_3. The iron precipitate was dissolved and reduced by zinc, and the iron estimated volumetrically. The ferrous iron was estimated volumetrically in a separate portion.

The following may be taken as representative of several sets of analyses.

	Light Colored	Dark Colored
SiO_2	1.56 per cent	1.56 per cent
Total iron, as Fe_2O_3	0.16	1.94
(FeO	0.12	0.45)
Al_2O_3	0.06	2.27
$CaCO_3$	94.02	71.03
$MgCO_3$	4.33	23.35
Total	100.13	100.15

The analyses show that nearly all the iron and alumina have been introduced with the Mg-bearing waters. The theory outlined above is consequently untenable. It may also be pointed out here that while in the light-colored limestone, where the ratio of the $MgCO_3$ to $CaCO_3$ is approximately 1:22, no recrystallization has taken place, in the darker stone, where the proportion is roughly 1:3, "dolomitization" has taken place, though the proportion required in a true dolomite is 1:1. This point will be again referred to in the discussion of the origin of the "dolomitization."

THE ORIGIN OF THE MOTTLING

If we exclude true brecciation as an explanation of the mottled effect of these limestones, there remains only one or other of two possibilities. Either the dolomitization has taken place practically simultaneously with the formation of the limestone, or subsequent dolomitization has ensued by water infiltration after a great thickness of the limestone has been laid down, and consolidation has taken place. Dixon, who has made a study of the dolomitization of the Carboniferous limestone of South Wales,[1] remarks on the difference between contemporaneous and subsequent dolomitization. He considers that subsequent or vein dolomitization is characterized by (*a*) larger average size and greater clearness of the rhombohedra, (*b*) inclusions of hematite, (*c*) association of dolomitization with calcification, (*d*) preference of dolomitization

[1] *Quart. Jour. Geol. Soc.*, XVII (1911), 477; and *Geology of South Wales Coalfields*, VIII (1907), 15 ("Memoirs Geol. Survey").

for oöliths and corals. In the case of vein dolomitization, calcification usually precedes dolomitization, the softer, abraded material being first attacked by water and recrystallized, while the Mg-bearing waters subsequently attack what has not been affected. Thus the parts that are affected by the Mg-bearing waters in subsequent dolomitization are just such as contemporaneous dolomitization would not affect—oöliths, corals, etc., the hardest parts in ordinary sediments but the softest in the recalcified rock. Judged by Dixon's tests, the pseudobrecciation of the Manitoba limestones is contemporaneous. There is no secondary calcification, the harder shells of corals, brachiopods, etc., have not been attacked in preference to the matrix, and the hematite is not included in the dolomite crystals. It seems difficult to imagine how subsequent dolomitization could affect a limestone in such a way that throughout a thickness of almost a hundred feet a uniform mottling should be produced, the affected areas being unconnected vertically. Leonard[1] seems to favor the view that the dolomitization in Clayton County is a subsequent phenomenon, in the sense that it was probably contemporaneous with the dolomitization of the Galena. This was inferred from the fact that the mottled limestones were found separating the fully dolomitized Galena from the underlying undolomitized Trenton in all cases except where impervious shales formed a sharp boundary line between the uniformly dolomitized and the non-dolomitized strata. The actual conditions are, however, different in Manitoba. Both the Lower Mottled and Upper Mottled limestones are overlaid by more completely dolomitized horizons—the Cat Head and the Stony Mountain formations—but a gradation from a mottled stone to a grey undolomitized limestone has nowhere been observed; nor can it be said that there is in any measure a gradation from a sparingly dolomitized variety by regular stages into a typical dolomite. The proportion of darker material is as great at the base of a section of mottled limestone 97 ft. thick as it is at the top.

CONTEMPORANEOUS DOLOMITIZATION

The evidence goes to show that the dolomitization in this area took place more probably as a practically contemporaneous

[1] *Loc. cit.*

phenomenon when the calcareous mud was as yet only partially solidified. We have then to account for the selective dolomitization of the calcareous ooze. Dolomite is formed according to the following reversible reaction:

$$2CaCO_3 + MgCl_2 = CaCO_3 \cdot MgCO_3 + CaCl_2$$

and the action is found to proceed from left to right when a temperature of 100° C. is reached. Increase of temperature accelerates the action. It is well known, however, that dolomitization has taken place, and is taking place today, where the proportion of Mg salt to Ca salt is much below that represented by the above equation. The process that goes on in nature is perhaps more accurately represented, as Klement has suggested,[1] by a continuous readjustment of equilibrium between the solution pressure of the solid $CaCO_3$ and the pressure of the Mg ions out of solution. Dolomitization would then ensue after the $CaCO_3$ had been precipitated; or, more correctly, a transformation takes place by which crystals of the optical characters of dolomite are formed, though the percentage of $MgCO_3$ may be smaller than that required for a true dolomite. In other words, dolomite is seemingly capable of forming mixed crystals—up to a certain limit—with $MgCO_3$, a substance not strictly isomorphous with itself. If then the reaction be stated crudely as $Mg'' \leftrightarrows Ca$, as an abbreviation for the statement that the two reactions $Mg'' \leftrightarrows Mg$ and $Ca \leftrightarrows Ca''$ are not independent, but regulate each other, three factors would affect the equilibrium: (1) percentage of Mg'' in the sea water, (2) temperature of the water, (3) character, though not of course the quantity, of the $CaCO_3$. An increase of Mg ions, and increase of temperature move the equilibrium point from left to right; while $CaCO_3$ in the form of aragonite is more readily affected, especially at moderately high temperatures, than is calcite, presumably because of the greater solution pressure of the $CaCO_3$ in the aragonite modification. In seeking for an explanation of selective dolomitization in the Manitoba limestones, one may practically discard the second and third factors. Local temperature changes may be neglected, except in so far as taken into account in a hypothesis outlined below, and there is no indication that aragonite shells have been attacked.

[1] *Tscherm. Min. Petr. Mitteil.*, XIV (1895), 530.

The proportion of Mg salts in ordinary sea water is very small (0.12–0.15 per cent Mg, increasing slightly with the depth). In inland seas, exposed to excessive evaporation, it may rise to 4.15 per cent Mg, as in the Dead Sea at 300 meters depth. Such exceptional conditions could not have prevailed; indications point to a clear, rather shallow sea, with recurrent periods of slight sedimentation. It may well be, however, as indicated by Steidtmann,[1] that the seas of the early Palaeozoic contained a slightly greater proportion of Mg salts than do similarly situated seas of today. The proportion of $MgCO_3$ in the paler-colored limestones shown by the analyses represents the amount of $MgCO_3$ that was deposited under normal conditions in these seas. It may be taken as the solid phase in equilibrium with the Ca and Mg salts in solution at that particular temperature and pressure, though undoubtedly a small proportion of the $MgCO_3$ was originally introduced as an ingredient in the composition of the calcareous shells. No recrystallization, and consequently no dolomitization in the strict sense of the word, has taken place. Presumably the $MgCO_3$ exists in solid solution with the very fine-grained calcitic material in which the broken shells are imbedded.

It would appear, then, that the dolomitization (with recrystallization) of the darker areas was due to the presence locally of a larger percentage of Mg salts than the normal. From this point of view three suggestions as to the cause of the dolomitization might be examined: (1) that algae, either as attached fucoids or as unicellular algae of the plankton, had contributed the necessary salts; (2) that the markings are due to worm castings; (3) that sea water inclosed in cavities, such as the interiors of shells, had dolomitized the neighboring rock.

The last of these suggestions we may consider first. Occasionally large shells are found in the center of the dolomitized areas, while no other trace of organic remains is to be found. If sea water replaced the softer parts of the organisms on their dissolution, and was retained till the layers were buried under a gradually hardening ooze, the slight rise in temperature and pressure might be sufficient, where undisturbed contact between the solid and

[1] *Jour. Geol.*, XIX (1911), 323.

liquid phases was preserved over a long period, to effect a gradual dolomitization. A concentration of magnesium salts in such a case is hardly possible, as evaporation could not have taken place; the result must be attributed entirely to long-continued favorable physical conditions. This is the explanation that first suggested itself; but it is hardly tenable. If such a process does actually take place, it is difficult to see why it should be the exception rather than the rule, as the possibility of inclusion of sea water in fossiliferous limestone, owing to the decomposition of the softer parts of the organisms, would always be fairly great.

Tracings of *Serpulites dissolutus* and of *Arabellites* sp. undet. have been identified in the limestones of the Lower Mottled division. It might naturally be suggested that the mottled effect in the limestones is due to actual castings of annelids, or to subsequent infillings of their borings. A well-known instance of the preservation, on a large scale, of annelid borings is that shown in the Middle and Upper Cambrian of the northwest Highlands of Scotland. In the Serpulite Grits and so-called "Fucoidal" beds, large trumpet-shaped depressions are found on the surface, which lead downward into vertical, cylindrical tube structures, much constricted in places. These are without much doubt the castings of annelids, the sudden constrictions and widenings representing the peristaltic movements of the intestines. Overlying these beds, limestones and dolomites 1,500 ft. thick are found, consisting in part of mottled beds (the "mottled" or "Leopard" stone of the Sailmohr group). Throughout the whole series fossils are rare, and the limestones, which contain numerous cherts, are attributed to the calcareous and siliceous remains of the plankton. The mottling of the limestone is due to the fact that the worm castings are dolomitized, and darker than the rest of the stone. According to Peach,[1] an explanation might be sought in the assumption either that the annelids were selective in their food, or that their gastric juices predisposed to dolomitization.

On contrasting the markings of the Upper Mottled with these, one finds two points of difference. In the limestones under discussion the markings are horizontally elongated, and irregular;

[1] Peach and Horne, and others, *The Northwest Highlands of Scotland*, p. 380.

in the Sailmohr the markings are vertical, rectilinear, and well defined. From the position and character of the markings, one may discard the theory that they are due to castings, which would in most cases be vertically disposed or grouped round definite centers. If taken simply as tracings, the difficulty in explaining the dolomitization still remains, and one is thrown back again on some such theory as the inclusion of water in the cavities left by the annelids. Although local dolomitization and mottling in limestone may in certain cases be attributed to annelids, one can hardly consider that markings of the kind found in the mottled limestones of Manitoba are due to this cause.

There remains the hypothesis that the mottling is connected with algic decomposition. Analyses due to Goedechens[1] show that the percentage of MgO in the ash of algae collected from the west coast of Scotland may reach 11.66. If then the algae of the sea bottom become buried under a thin coating of calcareous ooze before actual decomposition ensued, the liberated Mg salts might, in conjunction with the sea water of fairly high Mg content, cause such increase of Mg ions locally as to give rise to actual dolomitization. Only from such organisms and allied types could the percentage of Mg salts be increased locally to any appreciable extent. There are certain structural features of the markings that lend some support to this view of the origin of the dolomitization. They are horizontally placed, are markedly dendritic, and the sections often show a darker core which might represent the actual position of the plant; while the magnesian waters, extending outward from this central nucleus, have affected the surrounding stone. Again, thin sections of the dolomitized areas occasionally show a narrow central tube of clear, well-crystallized calcite (see Fig. 6), indicating that a cavity had existed when the dolomitization took place, and that this was subsequently infilled with calcite. Such cavities might be formed when, owing to decomposition, the organism disappeared. The hematite and limonite of the recrystallized dolomitic material would be attributed to the iron salts of the algae. Fig. 7 shows a normal cross-section, where no subsequent infilling has taken place.

[1] Pfeffer, *Pflanzenphysiologie*, I, 110.

Some of the difficulties in the way of the hypothesis may be referred to. A sea bottom in which a calcareous mud is gradually

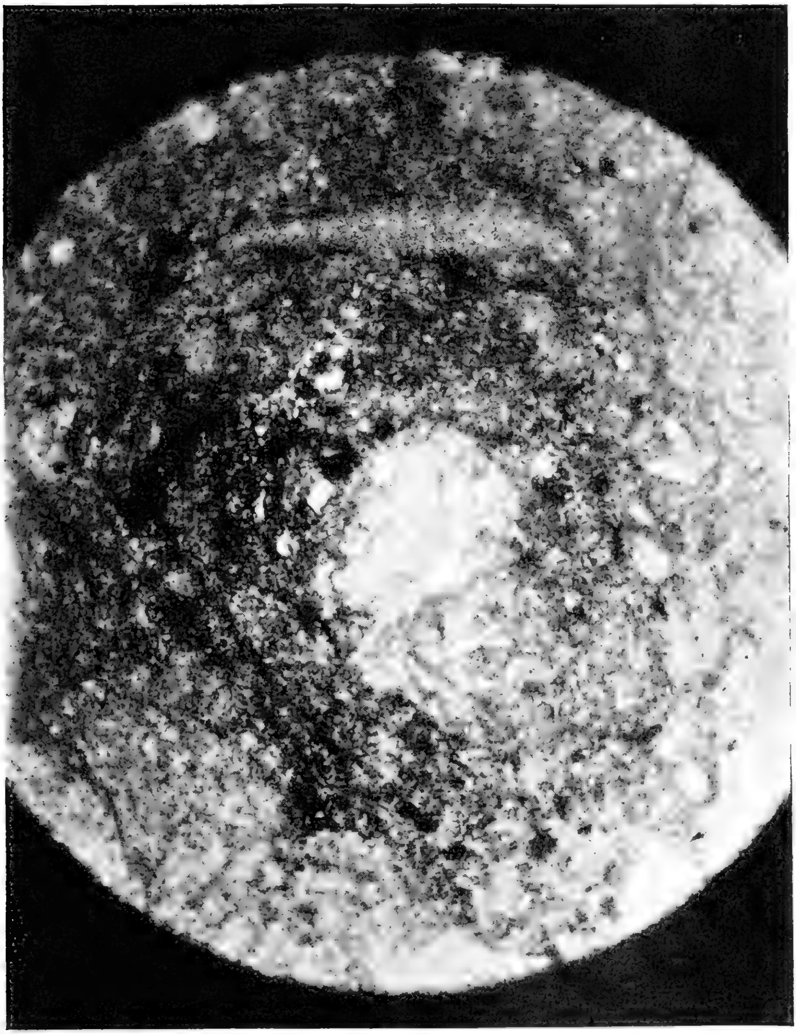

FIG. 6.—Dolomitized area with core of calcite. Border undolomitized. ×31

accumulating would not provide the rocky bottom necessary for algae in any way comparable to the laminaria of our seas; and a

profusion of vegetable growth would presumably be possible only in the shallower waters nearer shore. In the pre-Devonian rocks,

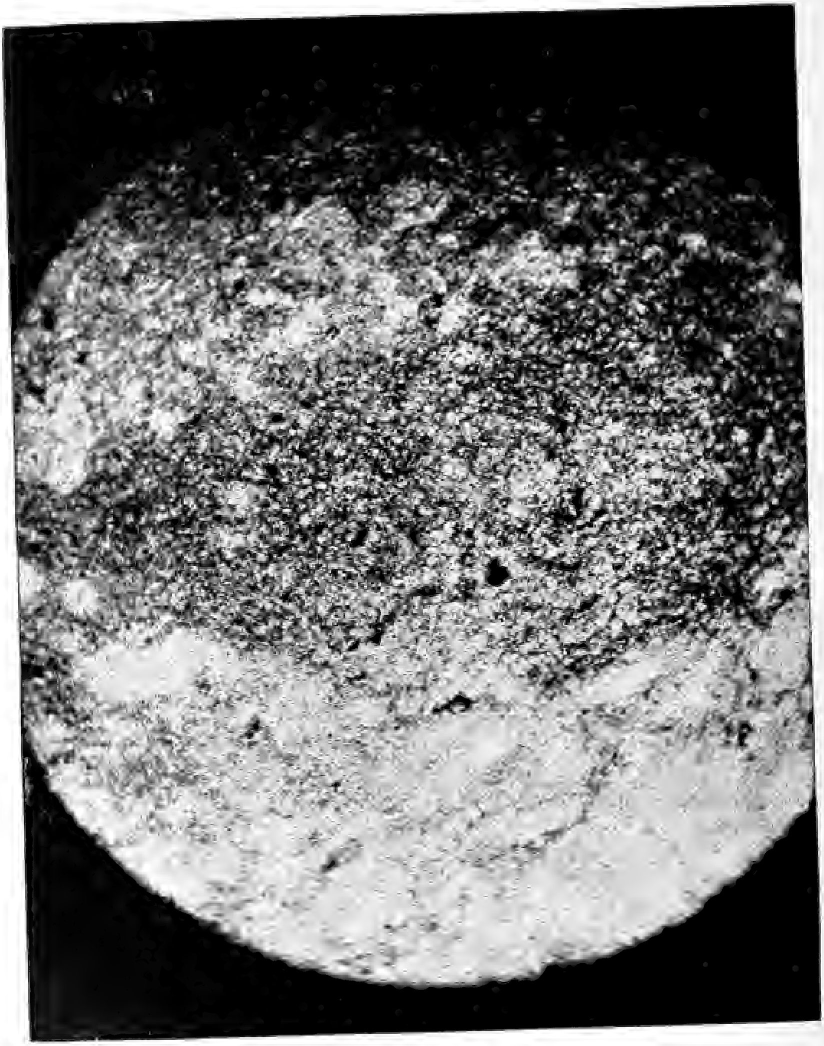

FIG. 7.—Section showing dolomitized area (center of field). ×31

definite impressions of fucoids are rare, though "fucoidal traces" have been the *dernier ressort* in cases of difficulty.[1] Unless when

[1] Seward, *Fossil Plants*, I, 139.

protected by a calcareous sheath, algae could be preserved only under exceptional conditions. We have, then, no definite knowledge of the development of attached algae in Ordovician and Silurian seas. In the strata in question, indisputable fucoids have been obtained only from the Cat Head and Stony Mountain beds, which are nowhere mottled, and are uniformly dolomitized. They are found as imperfect markings, and generally as raised impressions, and have been referred by Whiteaves to five distinct species of *Chondrites*.[1] Numerous unidentified markings on the bedding planes of the limestones have also been ascribed to fucoids.

If one may judge from the amount of carbonaceous material in rocks prior to Silurian times, it is probable that the algae had already attained a widespread development. The conditions which would give rise to dolomitization from plant forms which are so widespread in later seas must of course have been exceptional, and the chemical constitution of the seas of the period may provide the best explanation for the phenomenon. The evidence that has elsewhere been collected[2] goes to show that the percentage of magnesium salts in the early Palaeozoic seas was distinctly higher than in the ocean today. In the seas in which the Lower and Upper Mottled were laid down it was not sufficiently high to cause dolomitization in the sense that actual crystals with the optical properties of dolomite were produced; but the addition of magnesium salts from the decomposing algae was all that was required to start the process. Changing physical conditions—probably a shallowing of the sea—increased the Mg content at the time when the Cat Head and Stony Mountain formations respectively were being deposited, and in these formations a uniform, though by no means complete, dolomitization was effected. The algae may have drifted seaward from the rocky shores, and may have been fairly rapidly silted over. It is worthy of note that the presence of unicellular algae of the plankton has been confirmed in rocks of similar age in Wisconsin, and has been referred to, as already indicated, in the limestones of the upper Cambrian in the northwest Highlands of Scotland. The "oil rock" in the Galena of Wisconsin is found

[1] Geological Survey of Canada, *Palaeozoic Fossils*, III, Pts. 1 and 2.

[2] Steidtmann, *loc. cit.*

on microscopical examination to contain very numerous oval yellow bodies, which are interpreted by White[1] to be unicellular gelosic algae, probably comparable to the living Protococcales. The precipitation of the well-known lead and zinc deposits of this formation is attributed by Bain[2] to the reducing action of the hydrocarbons, and probably to hydrogen sulphide, resulting from the partial decomposition of the algae. Whether in the Manitoba limestones the mottling may be accounted for in part by unicellular algae settling in local depressions on the sea floor—caused for instance by the burrowings of annelids or other animals in the silt—the writer is not prepared to say. After reviewing, however, the hypotheses which may be advanced to account for a phenomenon the origin of which it is difficult indeed precisely to define, he is compelled to conclude that the evidence is strongly in favor of the theory that the decomposition of algae has been primarily responsible for the local dolomitization which is so marked a feature of these limestones.

SUMMARY

The irregular mottling which is a characteristic feature of two horizons of the Ordovician limestones in Manitoba is due to the presence of certain dolomitic areas in the limestone. The color contrast is caused by hematite and limonite filling the interstices between the dolomite crystals, rendering the affected areas much darker than the non-dolomitic.

The apparently brecciated structure is not truly clastic. The darker areas have been dolomitized *in situ* by Mg-bearing waters, working from the center outward.

Chemical analyses show that the iron salts have been carried in the waters which affected the transformation, and the iron minerals are not, as might be supposed from microscopical investigation, the result of the oxidation, when recrystallization took place, of ferrous carbonate held isomorphously in the calcitic material of the limestone.

The evidence in the field and laboratory is sufficiently convincing to lead one to conclude that the dolomitization is not a subse-

[1] *Wisconsin Geol. and Nat. Hist. Soc.*, XIX, 26.

[2] *Ibid.*, 142.

quent phenomenon—due to the percolation of Mg-bearing waters from above through considerable thicknesses of limestone along lines of weakness, but took place as a practically contemporaneous process with the formation of the limestone, in the upper layers of the calcareous ooze of the sea bottom.

A limestone may undergo uniform dolomitization when the percentage of Mg ions in the sea water affecting it is much smaller than the chemical equations usually taken to represent the process would demand. The percentage of Mg ions in the seas in which the Lower and Upper Mottled limestones in Manitoba were laid down was probably considerably higher than that in the sea today, but lower than that necessary to cause dolomitization such as the darker areas have undergone.

Under such conditions three factors would tend to produce local dolomitization: (1) local rise in temperature, (2) presence of aragonite in the calcareous ooze, (3) a greater percentage of Mg ions in the water permeating certain parts of the hardening ooze. The last factor is the preponderating one in the area under investigation.

Three suggestions are considered as possible explanations of the irregular dolomitization: (1) sea water included in the shells, replacing the decomposed softer parts of gasteropods, etc., has in time affected the surrounding rock; (2) the castings of annelids have become dolomitized in preference to the surrounding rock; (3) the limestone immediately surrounding decomposing algae has been dolomitized, the magnesium salts liberated from the algae being sufficient to raise the percentage of Mg ions in the sea water so far that recrystallization could take place.

The writer considers the third suggestion that which best explains the facts of the case. How far the effect is to be attributed to fucoids, and how far to unicellular algae of the plankton, one cannot definitely ascertain; but fucoids probably played by far the main part in contributing the necessary magnesian salts.

VARIATIONS OF GLACIERS. XVII[1]

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The following is a summary of the *Sixteenth Annual Report* of the International Committee on Glaciers.[2]

THE REPORT OF GLACIERS FOR 1910

Swiss Alps.—The summer of 1910 was extremely wet and snowy, which interfered materially with the measures of the glaciers; nevertheless it was found that the retreat is still general, although it is becoming less and less marked. Of the fifty-four glaciers measured, only two are actually advancing, namely the Sex Rouge and the Lower Grindelwald; some others show indications of possible advance; all in this class lie north of the Rhone and Rhine valleys.

Eastern Alps.—In this region also the wet summer interfered with observations. Two glaciers, in addition to the one mentioned last year, are advancing. In general, the glaciers are in retreat. Many ice avalanches fell in a part of the Oetztal, which was formerly free of ice.

Italian Alps.—The retreat here also is general. On account of the heavy snowfall some small glaciers were covered with snow to their ends during the whole summer, so that good observations could not be made. This was especially true of the Lombardy and Venetian Alps.

French Alps.—Many snow gauges have been set up by the French government and they show a decided increase in the snowfall in comparison with the average of the last ten years. At Sixt the snowfall was twice as great as the average. The quantity of snow which has come down in the form of avalanches is also materially greater. Although the glaciers in the *massif* of Mont Blanc, in the Tarentaise, in the Maurienne, and in the Dauphiné are all retreating, they seem to be increasing in thickness at the

[1] Earlier reports appeared in the *Journal of Geology*, III–XIX.

[2] *Zeitschrift für Gletscherkunde*, VI (1911), 81–103.

higher levels; and there is every indication of an approaching advance. The snow fields are increasing in size and vegetation is taking hold on the barren areas below the ends of the glaciers, indicating apparently a more moist climate.

Swedish Alps.—Of the five glaciers reported, all are apparently advancing.

Norwegian Alps.—In Norway a large number of glaciers are measured; during the last year the changes have been mixed, some advancing and some retreating, but an examination of the lists shows that on the whole the changes are distinctly toward an advance.

Africa.—Photographs of Kilimanjaro taken in 1898, 1904, and 1906 show that the glaciers on this volcano are retreating. A photograph taken in 1901 indicated an increased accumulation of snow in the crater, but in spite of this the glaciers are becoming smaller.

REPORT ON THE GLACIERS OF THE UNITED STATES FOR 1911 [1]

The Hallett Glacier shows no measurable change (Mills).

More snow than usual was found on the Arapahoe Glacier, but the end suffered a slight recession (Henderson).

Eliot Glacier on Mt. Hood continues its retreat (Langille).

Professor U. S. Grant and Mr. D. F. Higgins have continued their descriptions of some Alaskan glaciers.[2] Their latest observations were in 1909. They found that the Yale Glacier occupied about the same position as in 1899; that the Harvard Glacier had advanced a quarter to a half-mile, and the Bryn Mawr Glacier about 500 feet between 1905 and 1909. The position of the Barry Glacier is known for 1899, 1905, 1908, 1909; since 1899 it has retreated about 2 miles, and the rate of retreat seems to be increasing. Between 1905 and 1909 Toboggan Glacier advanced about 400 feet and then retreated about 650 feet. Many other glaciers were photographed

[1] A synopsis of this report will appear in the *Seventeenth Annual Report* of the International Committee. The report on the glaciers of the United States for the year 1910 was given in this *Journal*, XIX, 455–61.

[2] "Glaciers of Prince William Sound, and the Southern Part of the Kenai Peninsula, Alaska," *Bull. Amer. Geog. Soc.* (1910), XLII, 721–38; (1911) XLIII, 321–38, 401–17, 721–37.

and maps made of their ends. In general, where definite information was obtainable the glaciers proved to be in retreat, but some of them appeared to be advancing. Evidence was found of an advance of Columbia Glacier perhaps 50 years ago, and also of an earlier recession. About 1894 there was an advance, followed by a retreat. In 1905 the ice had retreated 160 feet behind its limit in 1899, but had regained 100 feet in 1908. Between July 15, 1908, and August 23, 1909, the ice advanced 380 feet.

Professor Lawrence Martin sends me the following account of the changes in a number of Alaskan glaciers between 1910 and 1911[1]:

Copper River.—The Childs Glacier, which advanced about 1,800 feet between the spring of 1909 and the autumn of 1910, for the most part in the season of 1910, moved forward 97 feet in the following eight months.[2] This movement, measured at the northern margin, where the glacier was only 1,474 feet from the Copper River and Northwestern Railway bridge in 1911, is at a much less rapid rate than during the previous summer, and the Copper River railway bridge is probably safe from the glacier during the closing stages of the present period of spasmodic advance; the river will probably always protect the bridge by undercutting the ice front during periods of rapid advance which come at high water, for the summer volume of the river is about equal to that of the Mississippi. This brief, spasmodic advance of Childs Glacier suggests the earthquake avalanche type seen 190 miles east in Yakutat Bay.

Miles Glacier, whose advance from 1908 to 1910 was 1,800 to 4,000 feet, in different portions of the ice cliff, had nearly ceased its rapid forward movement in June, 1911. The Grinnell Glacier continued during the winter of 1910–11 a slight advance, commenced the summer before. Allen Glacier showed no changes from 1910 to 1911. The Heney Glacier, which was stagnant for a long time before September, 1910, was newly crevassed and beginning to advance in June, 1911.

Southeast of Mt. Wrangell, the Kennicott Glacier, at whose margin a railway has recently been built, is stagnant and inactive, as it has been since before 1898. The Chitistone Glacier, some distance east of the Kennicott, is reported by R. F. McClellan to have advanced about half a mile during the winter of 1910–11.

Alaskan Range.—The Gulkana, Cantwell, Castner, and a large unnamed glacier near Rapids Roadhouse were inactive and retreating in 1911, as they have been for several years.

[1] See also Lawrence Martin, "The National Geographical Society Researches in Alaska," *Nat. Geog. Mag.*, June, 1911.

[2] In the table giving the variations of the Childs Glacier in the last report, "Advance in Feet" should be substituted for "Advance in Meters."

Prince William Sound.—Columbia Glacier, which advanced more than 1,700 feet between 1908 and 1910, has continued a slow forward movement, apparently due to climatic causes. The western margin advanced a little less than 100 feet from September 5, 1910, to June 21, 1911. The Valdez Glacier continued to retreat from 1910 to 1911, the amount of recession from June, 1909, to June, 1911, being reported by the late L. S. Camicia, of Valdez, as 36 feet.

Kenai Peninsula.—Spencer Glacier, close to the Alaska Northern Railway, retreated only 36 feet between January 8, 1906, and June 26, 1911. Glacier streams from this ice tongue have deposited outwash gravels so that twenty trestles in a distance of 1½ miles along the railway were filled and had to be abandoned. An elaborate and successful attempt to divert the glacial streams was carried out while the National Geographic Society party was at Spencer Glacier in June, 1911. As a result of the work of man in blasting a channel in the ice and producing two new subglacial stream courses, this glacier will probably retreat more rapidly in the next few years. Bartlett Glacier near the same railway is inactive and retreating.

Yakutat Bay.—A Boundary Survey party under N. J. Ogilvie visited Yakutat Bay in 1911 and took photographs from a number of sites occupied by Tarr and Martin in previous years. These photographs, furnished through the courtesy of Boundary Commissioner W. F. King, show the following: Nunatak Glacier, which retreated 2½ miles between 1890 and 1909 and advanced 1,000 feet the following year, made a further slight advance by the summer of 1911. The front of Hubbard Glacier had almost the same position in 1910 and 1911. The northern margin of Turner Glacier retreated slightly. The crevasses in Variegated Glacier, which was impassable in 1906, had so far healed by melting that in 1911 the Boundary Survey party traveled up the glacier to its head. Lucia Glacier, which was impassable in 1909, was traversed by the same party in 1911; so was Marvine Glacier, which was impassable in 1906.

Glacier Bay.—Muir Glacier retreated about 2,000 feet between 1907 and August 30, 1911. The thinning of the glacier by ablation and flow is an even more impressive feature than the retreat of the tidal ice front. It was possible, for example, in 1911, to walk upon a beach where, in 1907, there was an ice cliff, and where, in 1892, the ice was 1,200 feet thick. Tree stumps 12 to 18 inches in diameter, uncovered by the melting of the ice, show that the maximum advance of the eighteenth century was preceded by a minimum when Muir Glacier was even more emaciated than in 1911.

Other ice tongues in Glacier Bay which have continued receding are the following: Carroll Glacier had retreated so far that the eastern part of it did not touch the sea at low tide in 1911. A great delta had been built forward from nearly the middle of the ice cliff. Ablation had also removed the western distributary of Cushing Glacier, which previously spilled over to Carroll Glacier. Grand Pacific Glacier is retreating less rapidly than it did between 1899 and 1907, possibly because it is about to cease to be tidal. Johns Hopkins

Glacier is nearly separated into two independent ice tongues. Charpentier and Favorite Glaciers have been dismembered since 1906 by recession. Reid, Hugh Miller, Wood, and Geikie glaciers in Glacier Bay and Brady Glacier in Taylor Bay have changed less rapidly, though they are still receding.

La Perouse Glacier, west of Mt. Fairweather, and 130 miles southeast of Yakutat Bay, changed very little between 1910 and 1911, apparently having had in 1910 a brief spasmodic advance of the earthquake avalanche type.

In contrast with the other ice tongues of Glacier Bay, Rendu and an adjacent unnamed glacier have made notable advances. The former retreated about 2,000 feet between 1892 and 1907; it then advanced at least 8,350 feet and retreated again 600 feet by September, 1911. If the rate of the last retreat was about the same as the earlier one, the whole of the remarkable advance must have taken place in 1907. As Rendu Glacier is only 120 miles southeast of Yakutat Bay where nine or more glaciers have advanced since 1899 in response to earthquake avalanching, its advance may have been due to the same cause, and it will be interesting to see whether any of the other ice tongues of Glacier Bay push forward within the next few years. The small cascading glacier immediately south of Rendu Glacier has advanced a quarter-mile since 1907 and was discharging icebergs in 1911.

Southeastern Alaska.—Rainy Hollow Glacier, northwest of Lynn Canal, advanced more than 2,000 feet between June and September, 1910, as observed by the late Webster Brown. This brief, spasmodic advance in an ice tongue only 120 miles east of Yakutat Bay suggests the earthquake avalanche cause for activity. Davidson Glacier in Lynn Canal is still inactive; it changed little between the visit of G. K. Gilbert in 1899 and that of the National Geographic Society party in 1911. Eagle, Herbert, and Mendenhall glaciers, north of Juneau, which have recently been mapped in detail by the United States Geological Survey, seemed, as seen from a distance in 1911, to have suffered little change in recent years. Taku Glacier continued to retreat from 1907 to 1911. Norris Glacier, which was advancing and destroying vegetation when visited by F. E. and C. W. Wright in 1906, was advancing slightly and overriding shrubs in 1911. None of the ice tongues on the Stikine River displayed signs of abnormal activity in September, 1911. Popoff Glacier has retreated considerably since 1904.

The Kahiltna, Tokichitna, and Little Tokichitna glaciers, on the eastern side of the Alaskan Range, have large trees growing very close to their ends, indicating a stationary or advancing phase (S. R. Capps). But the glaciers on the western side of the range seem to be in retreat (Brooks).[1] About 30 miles east of Cape Yakataga the Malaspina Glacier has receded about 10 miles, leaving a good harbor (H. Horick).

[1] "The Mt. McKinley Region, Alaska," *Professional Paper 70, U.S. Geol. Surv.*, Washington, 1911.

THE EXTENT OF THE CORDILLERAN ICE-SHEET

CHARLES A. STEWART

Through the courtesy of members of the United States Forest Service I was enabled, in the summer of 1912, to make some observations upon glaciation in the Kaniksu National Forest in northern Idaho. Because of the inaccessibility of a part of the region and the lack of suitable maps, the work was not complete; but in view of our slight knowledge of the extent and character of the continental glaciation in the northwestern United States, and because the nature of the country makes it extremely unlikely that it will be more carefully studied in the near future, it seems advisable to publish the facts noted. Moreover, there was discovered evidence of more complete reworking of glacial deposits by stream action than has yet been described.

It is known that the front of the Cordilleran ice-sheet was marked by a series of marginal lobes occupying the north-south intermontane valleys of the northwestern United States. The line of crosses in Fig. 1, based on data published by Professor Salisbury,[1] shows the probable extent of some of these lobes. It is believed that the Pend d'Oreille lobe was continuous with that in the Colville valley, but its connection with the Kootenai lobe was well north of Bonners Ferry, and probably north of the International Boundary. In the paper cited nothing is said of the eastern boundary of the Pend d'Oreille lobe, but my observations show that the ice must have covered the divide between the Pend d'Oreille and Priest Lake valleys.

This divide is a range of forest-covered hills having a maximum elevation of 6,500 feet, and an average height a thousand feet less. The former presence of ice on these hills is unmistakably shown by the rounded topography, by *roches moutonnées*, and by glacial striae—in one instance on bedrock, and in others on float. The striae on bedrock strike N. 10° W. Looking east across Priest

[1] *Jour. Geol.*, IX, 721–24.

Lake from the top of this divide to the eastern shore of the lake, one sees the eastern line of the ice clearly marked. From this shore rises a series of hills with a smoothly rounded topography strongly indicating glaciation, but farther in the background is a higher ridge of granite, with a serrated and pinnacled outline in sharp contrast to the gentler slopes of the lower hills. Closer examination of this divide east of Priest Lake valley discloses a series of cirques worn out by valley glaciers tributary to the

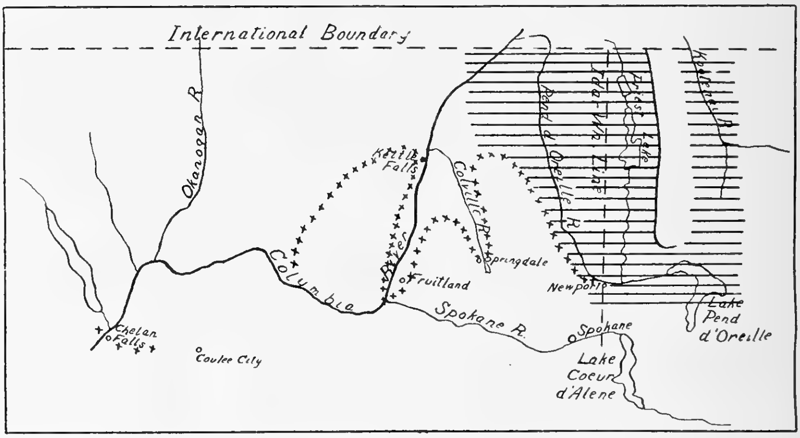

FIG. 1.—Sketch map of a portion of Idaho and Washington. Crosses indicate moraine according to Salisbury. Lined area shows extent of Pend d'Oreille–Priest River marginal lobe.

main ice-sheet. The upper limit of ice in these cirques was about 7,000 feet.[1] The Pend d'Oreille lobe therefore extended eastward as indicated by the lined area on the map.

The basins of Upper and Lower Priest lakes are deep and rock-floored, and suggest in all respects a valley scoured and enlarged by glaciation, and the lakes themselves can be attributed to no other cause than damming by morainal deposits. The country between the Upper and Lower lakes is low and swampy in most places, but deposits of coarse fragmental material are found; the outlet of the Lower Lake flows through a flat valley of sand

[1] All elevations given in this paper are based upon aneroid readings checked on U.S.G.S. elevation for Priest Lake 2,460 feet. As I was often away from this known elevation for several days, there is possibility of considerable error.

and gravel; and the streams flowing into the lake tumble over bowlder beds between banks of gravel and sand. It is noteworthy, however, that none of this detrital material—that separating the two lakes, that filling the main valley south of the lower lake, and that in the tributary valleys—shows any sign of morainal topography. It is arranged in terraces, somewhat modified by later erosion, but still forming distinctly flat-topped benches, and the bowlders and cobbles found in it indicate, by their partly rounded shape and the lack of striae, wear by water. The obvious conclusion is that upon the retreat of the ice this comparatively narrow valley was filled by a swollen, swiftly flowing stream that completely rearranged the morainal material. Mr. Calkins[1] has noted cases of similar reworking of glacial deposits east of here, but he found traces of true moraine. I know of no description of reworking of glacial deposits by stream action comparable in completeness to that at Priest Lake. An entirely similar condition was found at Sullivan Lake, a small mountain lake in Washington draining into the Pend d'Oreille River.

Having established the former existence of ice over the divide between the Pend d'Oreille and Priest Lake valleys, and its limitation on the east by the Priest Lake–Kootenai divide, we may consider the southern extent of this lobe. The Kootenai lobe probably extended to the southeastern lobe of Lake Pend d'Oreille,[2] but probably no farther, for there is no evidence of continental glaciation in the Cœur d'Alene Mountains immediately south of this lake. Glacial striae have been found at Cocollala, west of Lake Pend d'Oreille at an elevation of at least 200 feet above the lake.[3] It therefore seems probable that the ice of the Kootenai lobe, held back by the Cœur d'Alene Mountains on the south, spread westward down the Pend d'Oreille valley, and united with the Pend d'Oreille–Priest River lobe. The southern limit of the ice formed by the union of these two lobes was somewhere north of the outlet of Lake Cœur d'Alene if the conclusion that the gravel found there is an outwash plain is correct. It is possible, however, that this

[1] *U.S. Geol. Surv. Bull. 384.*

[2] Calkins, *ibid.*, p. 32.

[3] T. C. Chamberlin, *U.S. Geol. Surv., 7th Ann. Rept.*

material is reworked glacial material similar to that found at Priest Lake, and that the southern boundary of this lobe should be moved farther south. Mr. T. A. Bonser of Spokane, after a series of careful studies, believes that the ice extended at least as far as the city of Spokane, and occupied a part of the Spokane River valley. Until his results are published, however, we cannot definitely locate this southern boundary.

SUMMARY

The conclusions reached above are as follows:

1. The marginal lobe of the Cordilleran glacier occupying the Pend d'Oreille valley passed over the divide on the east and filled Priest Lake valley.

2. Salisbury's opinion is confirmed that if the Kootenai and Pend d'Oreille lobes were offshoots from a continuous sheet, their connection must have been north of the International Boundary.

3. The fronts of these two lobes united to form a continuous sheet of unknown extent to the south.

4. Fluviatile reworking of glacial deposits has been so extensive along the front of the Cordilleran ice-sheet that great caution must be used in marking the limits of glaciation. More careful studies will probably show that many localities in the Northwest which now show only the bedded bench gravels characteristic of water-work were at one time actually covered by the ice, and the line of the maximum extent of the Cordilleran glacier will have to be drawn farther south than it is at present.

AN EXPOSURE SHOWING POST-KANSAN GLACIATION NEAR IOWA CITY, IOWA

MORRIS M. LEIGHTON
University of Iowa

While collecting field data pertaining to the Pleistocene history of Iowa River, in Johnson County, Iowa, the writer recently examined a railway cut which furnishes some striking evidence, additional to that already presented by the late Professor Calvin, that a post-Kansan ice-sheet, much younger than the Kansan, invaded this part of the state of Iowa. It was thought, while this paper was being prepared, that no previous study of this interesting cut had been made, but Professor Shimek states that he examined the exposure some years ago.

The exposure is in a cut made in 1905 by the Cedar Rapids & Iowa City Interurban Railway. It is located $\frac{1}{8}$ mile northwest of the upper Interurban bridge across Iowa River and about 15 miles by rail northwest of Iowa City. The railroad grade here runs through the south end of a divide projecting somewhat into Iowa River valley, the summit of the divide at the surface of the cut being about 30 feet above the valley flat. The physiographic setting is shown in Fig. 1. This is within the area mapped as Iowan drift by Calvin.[1]

The cut is about 250 yards long and attains a maximum depth of 20 feet. For about 120 yards, the east end is till, and for 100 yards at the west end the material is yellow fossiliferous loess. Between these are contorted folds and rolls of Buchanan gravel in peculiar relation to the Kansan till below and overlain by 2 to 8 feet of till. The arrangement of the materials is shown in Fig. 2.

The oldest material in the cut is Kansan till—blue at the bottom and grading up in places into a grayish to yellow color according to the degree of weathering. The blue is very clayey, contains small pebbles, many of which are greenstone, and breaks with polyhedral

[1] Samuel Calvin, *Iowa Geological Survey*, VII, opposite p. 92.

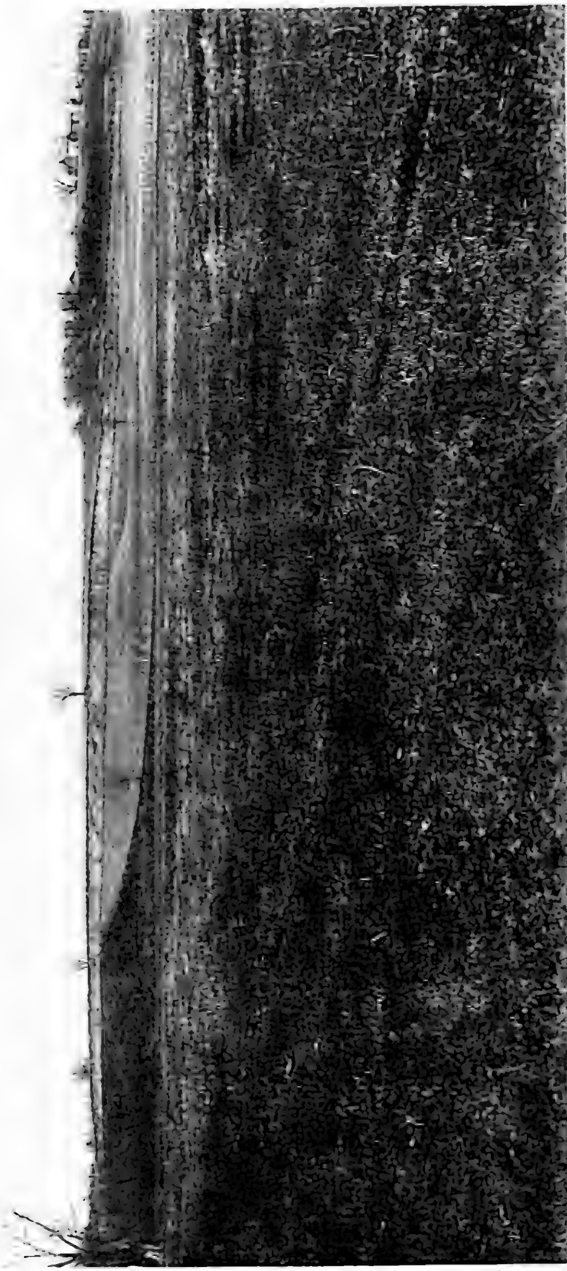

FIG. 1.—View looking north, showing the physiographic setting of the cut. The rolls can be faintly seen to the left of the east lone tree, on top of cut.

fracture. Joints are prevalent in the yellow clay and in the upper part of the blue, but instead of being vertical they dip toward the west, suggesting that they are the result of pressure from that direction. In that case they might be regarded as slight shear planes resulting from the same force that produced the distortion of the gravel above. Overlying this, in a peculiarly folded and contorted manner, is Buchanan gravel, the textural range of which is from fine flour to bowlders 1 foot in diameter. The gravel exhibits the usual oxidized, weathered, and decayed character. Ironstones are not uncommon and cementation by iron oxide is sufficiently prevalent to have preserved stratification lines at many points.

At the west end of this section (left end of Fig. 2), the gravel appears in a narrow band in the lower part and rises to the east at an angle of about 45 degrees, reaching a height of 16 feet. From this point the gravel follows a horizontal course eastward for about 75 feet and ends rather abruptly against till.

FIG. 2.—View of the north face of Interurban cut, 15 miles northwest of Iowa City, Iowa, showing the arrangement of Buchanan gravel on Kansan till and overlain by a later till. The numerical index is referred to in the text.

In this middle portion there is a peculiar series of contortions in the gravel. Reference to the photograph shows that (2) and (3) are two small, almost perfect, synclines of the closed type; (4) is a large, elongate body 27 feet long with an accumulation of small bowlders and gravel at the east end; (5) is a small elliptical roll having a nucleus of gravel with wrappings of till, all of which is surrounded by till; (6) marks a protruding compact body of gravel that has withstood slope-wash; (7) is a large downward loop 7 feet deep; and (8) and (9) appear as stringers projecting from the main body of the gravel into the till below.

At (1) and around the lower part of (7), the gravel, so altered that some cobbles can be picked to pieces by the fingers, rests against the blue unweathered till, and along the lower contact of (4) and around the lenticular body (5), the edge of a knife-blade can mark the separation of the oxidized gravel from the much less oxidized till. Till that is scarcely changed lies high in the arches between (7) and (8), and between (8) and (9). It is also striking that the gravel deep in the cut is as much weathered as that near the surface.

Overlying the gravel is a yellow, blue-streaked till, 2 to 4 feet thick across the summit, and attaining a thickness of at least 8 feet along the west monoclinal limb. On the western slope of this, beginning at the point (*x*) and lying in contact with the drift along a diagonal line (made clearer by dotting), lies yellow, fossiliferous loess which is not contorted but which shows deposition after the disturbance of the gravel. This body of loess is in the west end of the cut.

INTERPRETATION

To account for such folds, rolls, and contortions of Buchanan gravel into Kansan till in such a way as is revealed here, there can be but one possible interpretation. The sharp contact of the oxidized, altered, and rotten bowldery gravel upon unchanged till at points (1) and (7), and between (7) and (8), and between (8) and (9), and the sharp break below the elongate body (4) and around the lens (5) prove that the folding took place after the gravel was weathered. If the weathering had taken place since their disturbance, there should be at least a narrow gradation-zone between

the weathered and the unweathered portions. Such, however, does not occur. Besides the foregoing significant relations, the gravel is uniformly weathered at different depths, but the till is not.

The conclusion is therefore clear that an ice-sheet, capable of distorting and molding this hill of material, invaded this region after the Buchanan gravel and some of the Kansan till were much weathered.

In view of the above interpretation there are four important points embodied in this cut: (1) the Kansan drift and the Buchanan gravel record the invasion and retreat of the Kansan ice; (2) the weathering of the same represents a considerable time interval after the Kansan invasion; (3) the contacts record the close of that interval and the folds give identity to the presence of a later ice-sheet and its movement; (4) the yellow loess, at least in this exposure, was deposited subsequent to the advance and retreat of the later ice-sheet.

RECONNAISSANCE IN THE SOUTHERN WASATCH MOUNTAINS, UTAH[1]

G. F. LOUGHLIN
United States Geological Survey

CONTENTS

INTRODUCTION

The facts here presented were gathered during a reconnaissance of the ore deposits in central Utah for the United States Geological Survey during the summer of 1912. No time was available for thorough areal work, but certain of the results obtained in the southern half of the Wasatch Mountains seem to be of sufficient interest for presentation. The districts visited in the Wasatch country were the Big and Little Cottonwood districts, where the writer accompanied Mr. B. S. Butler of the Survey, the American Fork and Alpine districts, the Provo district, and the Santaquin–Mount Nebo district (see Fig. 1).

Previous work.—The only published accounts of previous areal work on the bedrock geology of the region are in the report of the

[1] Published by permission of the Director of the United States Geological Survey.

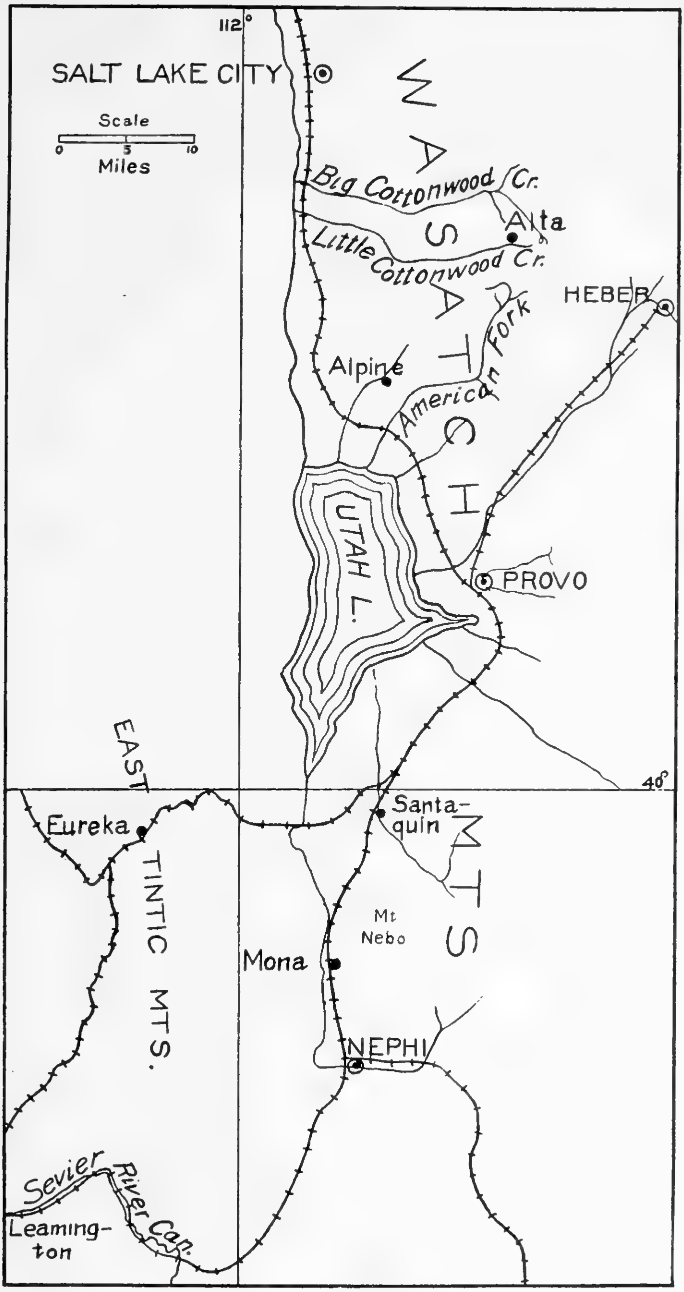

FIG. 1.—Sketch map showing positions of places mentioned in the text

Fortieth Parallel Survey, and that on the Park City mining district by Boutwell. Mr. F. S. Emmons, of the Fortieth Parallel Survey,[1] mapped the geology of the Wasatch Mountains from Provo Peaks northward, and his report gives brief mention of Mount Nebo 25 miles farther south—the highest and southernmost peak of the range. Mr. Emmons had only three weeks for his entire work in the Wasatch Mountains, and the amount of ground covered and the great quantity of data gathered by him in that time are indeed wonderful. It is only to be expected that his traverses did not lead him to all the places where the clues to stratigraphy and structure were exposed, and that in the absence of those clues certain evidence could not be finally interpreted. It is, however, a relatively easy matter for one aided by the Fortieth Parallel map to investigate certain special problems and to find evidence which modifies the interpretations originally given.

Boutwell has done considerable work in the country around the Cottonwood and American Fork districts,[2] and has thrown much light on the geology of both the igneous and sedimentary rocks; but his published detailed work on the latter deals chiefly with formations stratigraphically higher than those considered here, and the detailed descriptions of structure are confined to an area farther east than that visited by the writer. Boutwell, however, was the first to recognize overthrust faulting in the Wasatch Mountains.[3]

Blackwelder in 1910[4] made some interesting contributions to our knowledge of the northern Wasatch Mountains, eliminating the "Ogden (Devonian)" quartzite of the Fortieth Parallel Survey and discovering several great overthrust faults. He also examined the Big Cottonwood Canyon section and found an unconformity in the great quartzite series, correlating the overlying 1,500 ft. of the quartzite as Cambrian and the underlying 10,500 ft. as Algonkian.

[1] *U.S. Geol. Explor. of the Fortieth Parallel*, II (1877), 342–66.

[2] J. M. Boutwell, "Geology and Ore Deposits of the Park City District, Utah," *Prof. Paper 77, U.S. Geol. Survey*, 1912.

[3] J. M. Boutwell, "Stratigraphy and Structure of the Park City Mining District, Utah," *Jour. Geol.*, XV (1907), 456–57.

[4] E. Blackwelder, "New Light on the Geology of the Wasatch Mountains, Utah," *Bull. Geol. Soc. of America*, XXI (1910), 517–42.

The results here presented are essentially a sequel to Blackwelder's work. To avoid repetition the evidence will be considered by districts rather than according to stratigraphy and structure.

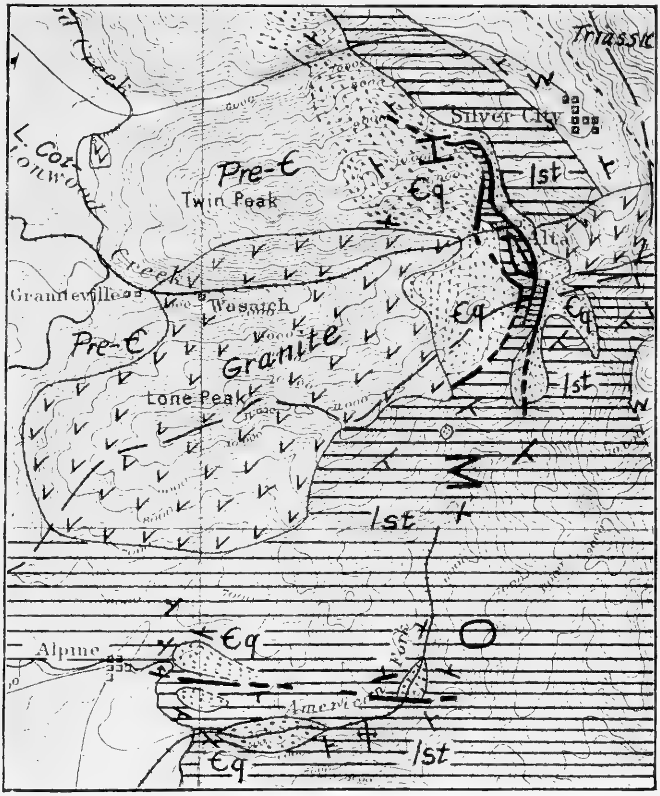

FIG. 2.—Geologic map showing the intrusive granite (probably post-Jurassic), Cambrian quartzite (-Єq), and the great Cambrian to Mississippian limestone belt (*lst*) in the Cottonwood and American Fork–Alpine districts. The width of the narrow "lower" limestone belt at Alta is somewhat exaggerated. *W* = Weber quartzite; *Pre*-Є = pre-Cambrian. Topographic base taken from the Salt Lake sheet, United States Geological Survey.

THE COTTONWOOD DISTRICT[1]

Structure.—The arrangement of formations in this district is, as shown in Fig. 2, and more completely on the Fortieth Parallel

[1] The term Cottonwood district is here used to include the area around the upper parts of Big and Little Cottonwood canyons.

Survey map, a rudely elliptical mass of granite surrounded on three sides by a concentric succession of sedimentary rocks. The granite, originally called Archean, was proved by Mr. Emmons in 1903[1] to be intrusive and probably of post-Jurassic age and his conclusions have been sustained by Boutwell.[2] The sedimentary rocks were originally correlated as follows:

Permo-Carboniferous and later
Upper Coal Measures limestone
Weber quartzite, Carboniferous
Wasatch limestone (intercalated series at the top), mostly lower Coal Measures
Ogden quartzite, Devonian
Ute limestone, Silurian
Quartzite (clay slates at the top), Cambrian

The present writer, however, during his first day in the district found fossils in the lower limestone belt (called the "Ute" in the above table) of Madison (Lower Mississippian) age. These fossils were collected on the spur between the two cirques just over the divide northwest of Alta, and were determined by Dr. Girty of the Survey as follows:

Syringopora sp.	Syringothyris (?) sp.
Zaphrentis sp.	Composita sp.
Amplexus sp.	Cleiothyridina crassicardinalis
Spirifer centronatus	Euomphalus sp.

These fossils are in part duplicated by fossils found in the great upper limestone belt (the "Wasatch" limestone of the Fortieth Parallel Survey), the greater part of which appears to be of Madison age. The fossils collected from this belt were determined by Dr. Girty as follows:

Syringopora sp.
Zaphrentis sp.
Spirifer centronatus

The presence of two belts of Mississippian limestone separated by a quartzite belt at once suggested the presence of an overthrust fault, which is proved by the following evidence. The "lower" limestone extends northward for about half-way down the Mill D

[1] S. F. Emmons, *Amer. Jour. Science*, 4th series, XVI (1903), 139–47.

[2] J. M. Boutwell, *op. cit.*, p. 156.

South Fork of Big Cottonwood Creek, where it appears to be overridden by the "upper" quartzite (the "Ogden" in the above table), which here rests directly, though discordantly, upon the lower (Cambrian) quartzite. The "lower" limestone is absent to the northwest in Big Cottonwood Canyon. Southward from Alta the "lower" limestone extends in a synclinal attitude between the two quartzite belts as far as the head of American Fork Canyon, where it passes through a complication of faults and local contortions and finally merges into the great "upper" limestone belt (see Fig. 2). Middle Cambrian fossils found by Mr. Butler in shale members of the "upper" quartzite both north and south of Alta confirm the structural evidence of an overthrust. These fossils were determined by L. D. Burling as follows:

Zacanthoides cf. spinosus
Obolus (westonia) ella
Micromitra (Iphidella) pannula

The overthrust structure, however, is complicated by two or more later fault systems. The older and more conspicuous of these was evidently developed by the stresses induced by the granite intrusion. The intrusion effected a domal uplift of the Paleozoic and Mesozoic rocks, and the force was great enough to rupture the dome in places, forcing the more central portions upward and outward against the outer portions. The strongest of these faults is best exposed on the north side of Little Cottonwood Canyon about half a mile west of Alta (Figs. 2 and 3), where the "lower" quartzite and shale, badly contorted, abut against the "lower" limestone along a steep westward-dipping fault plane. A second similar, but smaller, westward-dipping reverse fault is exposed about three-fourths of a mile east of the first, along the divide between Little Cottonwood Canyon and Mill D South Fork. The effects of these later reverse faults in obscuring the earlier overthrust are shown in Fig. 3. Both of the later reverse faults die out northward along the strike rather rapidly; southward the same, or similar, parallel faults are exposed near the head of American Fork Canyon, and the western one (nearer the granite) appears to continue in a southwestward direction as far as the Silver Lake cirque, beyond which the quartzite belt is cut off by the intrusive granite.

Besides these later reverse faults there are still later normal faults, some of which parallel the reverse faults and serve further to complicate the structure. Only one is indicated in Fig. 3. Some of the normal faults are mineralized, but as the writer's four-day visit to the district was almost wholly confined to surface work, he cannot consider them further than to state that the few veins seen by him, some of which lie along well-defined faults, appear to bear a radiating and concentric relation to the granite mass. Mapping of all the veins in the district may disprove this

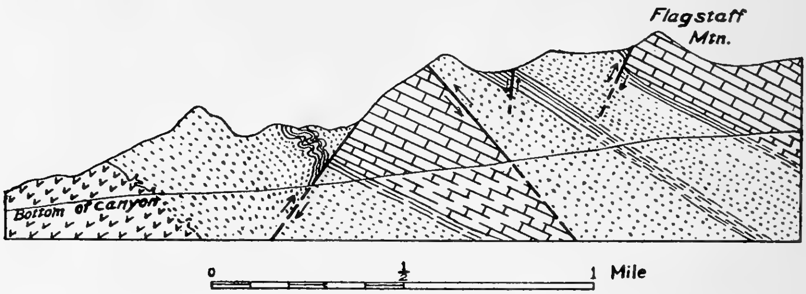

FIG. 3.—N.E.–S.W. section on the northwest side of Little Cottonwood Canyon, northwest of Alta, showing the effect of faulting upon the distribution of the Cambrian quartzite and the Cambrian to Mississippian limestones. The east-dipping overthrust is the oldest, the west-dipping reverse faults are later and directly related to the intrusive granite shown at the left. The normal fault in the central part is only one of several which were not mapped in detail.

hasty statement. Whether or not there are important faults still later than the period of mineralization the writer cannot say.

It may, however, be well to emphasize the relations of the two limestone belts to the distribution of ore bodies. Both belts contain producing mines, and during the writer's visit, in July, 1912, it is said that certain companies operating in the eastern or "upper" limestone belt were planning to sink to the "lower" belt in the hope of finding new ore bodies. The presence of the overthrust faults, as shown in Fig. 3, gives such a plan little hope of success. It cannot yet be said just how far the overridden belt extends eastward beneath the "upper" quartzite, but it is highly probable that it pinches out within a rather short distance.

Summary of structural evidence.—The "lower" limestone, formerly called the "Ute (Silurian)" by the Fortieth Parallel Survey, is proved to be a part of the Mississippian and older limestones overridden by a slab of the Cambrian quartzite which was formerly called "Ogden" and referred to the Devonian. This overthrust of eastward dip, was broken by at least two parallel reverse faults of steep westward dip which were formed during the domal uplift which accompanied the granite intrusion. Still later normal faults further complicate the structure.

Stratigraphy.—The stratigraphy east of the reversed faults, or from the "upper" quartzite belt upward, consists of a thin belt of Cambrian shale, which grades upward into the great limestone belt. The lowest limestone beds may be Cambrian also, but the greater part of the limestone contains Mississippian fossils. No careful measurements of thickness were made, but a rough estimate shows that there cannot be much more than 2,000 ft., and maybe much less, of pre-Mississippian limestone and shale. This is in marked contrast to the stratigraphy in the northern Wasatch Mountains and in the Uinta Mountains to the east. In the former, Cambrian limestones and shale above the quartzite aggregate 5,415 ft.[1] and are themselves separated from the Mississippian by 1,000 to 1,200 ft. of Ordovician and 1,000 to 1,500 ft. of Silurian and Devonian limestones.[2] In the latter, on the contrary, the entire great limestone belt is only 700 to 1,000 ft. thick, and Weeks[3] correlates its lowest beds with the Mississippian. The upper part he assigns to the Pennsylvanian. The Silurian and Devonian have been shown by Weeks and Ferrier[4] to thin southward and eastward, and they may not be represented so far southward as the Cottonwood district; but the exact stratigraphic relations cannot be accurately determined by mere reconnaissance work.

[1] C. D. Walcott, "Cambrian Brachiopoda," *Mon. U.S. Geol. Survey*, No. 51, Vol. I (1912), 148–52.

[2] E. Blackwelder, *op. cit.*, pp. 527–28.

[3] F. B. Weeks, "Stratigraphy and Structure of the Uinta Range," *Bull. Geol. Soc. America*, XVIII (1907), 432–41.

[4] F. B. Weeks and W. F. Ferrier, "Phosphate Deposits in Western United States," *Bull. U.S. Geol. Survey*, No. 315 (1906), p. 451; F. B. Weeks, "Stratigraphy and Structure of the Uinta Range," *Bull. Geol. Soc. America*, XVIII (1907) (correlation table). Silurian and Devonian are not represented in the Uinta Range.

The Mississippian limestone is followed upward by a considerable thickness of limestone, shale, and sandstone, which is succeeded by the Weber (Pennsylvanian) quartzite, and the Weber in turn is overlain by the Park City (Permian?) and Mesozoic formations. No measurements of the thickness of any of these formations were made.

THE AMERICAN FORK–ALPINE DISTRICT

The strata along upper American Fork Canyon south of Mary Ellen Gulch are almost entirely of the great limestone belt, striking about parallel to the neighboring granite contact and dipping away from it (see Fig. 2). The dip undulates gently, and at one place erosion has evidently exposed the top of the quartzite, presumably along a low anticlinal flexure; but the one quartzite outcrop found is completely isolated in an area of glacial drift, and its structural relations can only be inferred. Near the great bend in American Fork Canyon the uniformity of strike and dip is interrupted by an anticlinal or domal structure in which the Cambrian quartzite is exposed along the lower canyon walls. The southern part of the dome is cut off by an E.-W. fault, with relative upward movement on the north side. Two miles below the bend, the quartzite is again exposed along the lower canyon walls in a second domal uplift. About midway between this second dome and the town of Alpine to the northwest, the quartzite is again exposed in a third domal uplift, which like the first is broken by a fault. The fault is exposed along the range front and is clearly of the reversed type, with steep northward dip (toward the granite). As these faulted dome structures are essentially small duplicates of the great faulted dome around the intrusive granite, they may indicate the presence of unexposed intrusive granite bosses south of the exposed granite area. This suggestion is strengthened by the fact that the southern granite contact pitches southward beneath the contact-metamorphosed limestones. The southerly pitch is well shown at the Silver Lake cirque about 4 miles east of Lone Peak, where limestone forms the west wall, and quartzite and limestone the east wall, but where granite forms the north wall and the floor.

The quartzite exposures in American Fork Canyon were regarded as Devonian by the Fortieth Parallel Survey, as their

exposed thickness was not too great and no other quartzite occurred above them; but since they have the same stratigraphic position as do the fossiliferous Cambrian "upper" quartzite and shale in the Cottonwood district, there can be no reasonable doubt of their Cambrian age. There are several good exposures of shale just above the quartzite areas, and it is in these that fossils are to be expected. South of American Fork Canyon the strata pitch southward, and along the west foothills of Timpanogos Peak, east of Pleasant Grove, the Mississippian limestone reaches nearly or quite down to the level of the Lake Bonneville shore line. Timpanogos Peak was not ascended.

THE PROVO DISTRICT

As only one short day was spent at Provo, remarks will be limited to the two quartzite occurrences along the lower front of Provo Peaks. They are both exposed along anticlines which are in line with each other, but oppositely unsymmetrical. The northern exposure forms a low arch for about 3 miles along the range front, and is nearly bisected by the mouth of Rock Creek Canyon, northeast of Provo. Near the mouth of the Canyon the quartzite is flanked by a still lower body of dark argillaceous limestone, which at the mouth of the canyon is faulted against it. No fossils were found in the limestone, and its physical characters were of too indefinite and general a character to permit a definite correlation with any members of the great limestone belt above the quartzite, though such a correlation is possible. It is also possible that this lower limestone is intercalated within the quartzite. Pebbles of impure limestone were found in a dark conglomerate bed in the quartzite at the canyon mouth, but represented, on weathered surface, a light-gray, finely banded type and not the dark type in question. The pebbles, however, indicate the presence of limestone in Cambrian or earlier time, and an unconformity possibly within the Cambrian.

The quartzite and its overlying shale have a gentle eastward dip for a short distance, but just above the mouth of the canyon they steepen abruptly and are slightly overturned, dipping 80° westward. The great limestone belt lies above the overturned portion

with a very gentle and uniform easterly dip, as if it had slid bodily westward over the quartzite and shale; but, as the writer entered the canyon at sunset he had no opportunity to get more than a hasty glance at the structure. Mr. Emmons remarked that the structure, as seen from the canyon bottom, appeared to be a strong unconformity, but that examination the whole length of the canyon proved the structure to be an S-shaped fold with only its upper half exposed.[1] The limestone cliffs show the same succession of limestones as that which overlies the Cambrian quartzite and shale in the Cottonwood district, and the quartzite exposures at Provo are therefore to be assigned to the Cambrian, and not to the Devonian as was done by the Fortieth Parallel Survey.

The southern quartzite occurrence, southeast of Provo, also forms an arch along the range front, cut by Slate Creek Canyon. In this case, however, the western limb is very steep. The quartzite is exposed approximately along the axis and is flanked by overlying limestone dipping steeply westward. The east limb, which can be studied along the walls of Slate Creek Canyon, dips very gently and is overlain by about 200 ft. of shale and the regular succession of limestone beds. The conglomerate bed with light-gray limestone and other pebbles is exposed in the canyon near its mouth, and beneath it in the creek bed is a doubtful outcrop of dark bluish-black limestone similar to that flanking northern quartzite exposure. The evidence in the two cases, though not absolutely convincing, is thus consistent and points to the existence of a local limestone horizon below, or within, the quartzite, and also to the existence of an unconformity below the exposed part of the Provo section, presumably in Lower Cambrian time.[2] Limestone beds of Middle Cambrian, and one small bed of Lower Cambrian or even earlier age, were found by the writer intercalated in the great quartzite series of the Simpson Mountains north of the

[1] *Op. cit.*, pp. 345–46.

[2] According to Walcott ("Cambrian Sections of the Cordilleran Area," *Smithsonian Inst. Misc. Coll.*, 1908), the first 100 ft. of shale above the basal quartzite in Big Cottonwood Canyon are Lower Cambrian and next 150 ft. are Middle Cambrian. The quartzite at Provo, 25 to 30 miles farther south, may therefore also be regarded as approximately at the top of the Lower Cambrian.

Sevier Desert in June, 1912, but none farther east are known save this obscure Provo occurrence.

THE SANTAQUIN–MOUNT NEBO DISTRICT

Santaquin is about 18 miles S.S.W. of Provo. The Wasatch Range from here southward to Mount Nebo is interesting both from a stratigraphic and structural standpoint.

Stratigraphy.—The oldest formation in the district is a band of pre-Cambrian gneissoid granite with large included bodies of schists, exposed for 2 miles or more along the lower range from east of Santaquin. It is quite different in texture from the granite of the Cottonwood district, and is overlain unconformably by Cambrian quartzite, the basal beds of which contain quartz and coarse red feldspar fragments derived from the pegmatitic facies of the granite. The quartzite formation dips 28° east and does not appear to be over 800 ft. thick. It varies in texture from conglomerate to shale, and in color from white to dark red and brown. In its upper half are a few dark-green beds with a high iron content. The quartzite passes upward into shale in which Cambrian trilobites have been found. The shale is followed by alternating beds of argillaceous limestone and shale, and finally by continuous limestone which at the top of the ridge includes a part of the upper Mississippian "intercalated series."

The Mississippian limestone is abundantly fossiliferous, and the lowest Mississippian fossils were found at a horizon about 2,400 ft. above the top of the quartzite. No fossils in the intervening limestones were found, but the lithologic succession as a whole is very similar to that of the lower half of the limestones of the Tintic district, about 20 miles to the southwest, which total 3,500 ft. in thickness and are chiefly or wholly Cambrian. No unconformity was detected, but so far as comparisons can be made the Mississippian limestones in the Santaquin, as well as in the Cottonwood district, lie on a much thinner series of limestone than is the case in the Tintic district to the west or in the northern Wasatch Mountains.

The upper Mississippian "intercalated series" is overlain unconformably on the east flank of the ridge by a coarse reddish

conglomerate, part of which consists of quartzite, chert, and limestone pebbles, and part of calcareous beds full of peculiar concretionary growths. Some of these concretions resemble shells in form, and one undoubted gastropod was found, which Dr. T. W. Stanton of the Survey says may be a fresh-water Eocene species. The unconformity implies the removal by erosion of the Weber quartzite, the Park City formation, and the Mesozoic formations which overlie these formations in the Park City district. Overlying the Eocene conglomerate is a coarse andesitic (or latitic) breccia. Its outcrops are weathered and largely reduced to aggregates of loose cobbles some nearly a foot in diameter, and the nature of its contact with the underlying conglomerate, whether conformable or unconformable, could not be determined.[1] Intrusive volcanic rocks are limited to a few dikes, also of andesitic or latitic character.

In the low hills south and southwest of Santaquin, a veneer of Eocene conglomerate with remnants of the volcanic breccia overlies limestones of pre-Mississippian (probably Cambrian) age, and 35 miles farther southwest, in the Sevier River Canyon, the same Tertiary sequence of rocks rests unconformably upon the Cambrian quartzite. Nearly the whole Paleozoic, as well as the Mesozoic, section in central Utah is thus beveled off by this unconformity, as is the case in the Uinta Mountains in northeastern Utah.[2]

The last two Eocene occurrences mentioned are somewhat farther west and north than any previously mapped, and it is believed that they are not far from the original limits of the Eocene in this region; for in Long Ridge and the East Tintic Mountains, about 12 miles southwest of Santaquin, the same type of andesitic breccia rests either directly upon Paleozoic rocks, or is separated from them by an intervening body of effusive rhyolite, and no sedimentary rocks later than Paleozoic have been found.

Structure.—The principal structural features in the Santaquin–Mount Nebo district are faults, including doubtful overthrusts of

[1] C. K. Leith and E. C. Harder. (*Bull. U.S. Geol. Survey*, No. 338 (1908), pp. 18 and 21) have proved an unconformity between Cretaceous and Eocene beds in the Iron Springs district of southern Utah and a later unconformity between the Eocene beds and Miocene lavas.

[2] F. C. Weeks, *op. cit.*, p. 442.

N.-S. trend and a series of N.-S. and E.-W. block faults of the Basin Range type (see Fig. 4). The former are so poorly exposed, their courses so nearly parallel to the N.-S. system of the block faults, and, in some places, the rocks along them so free from severe crumpling or crushing, that the writer is not fully convinced of their overthrust character.

Overthrusts: East of Santaquin the northern part of the pre-Cambrian granite appears to overlie quartzite, but the contact is concealed by float. A little farther northward, however, the granite pinches out and the main body of Cambrian quartzite overlies a dark brecciated limestone, which passes downward into shale and quartzite. This lower quartzite exposure, in turn, overlies fossiliferous Mississippian limestone, which is very free from any of the crumpling or brecciation which is likely to accompany overthrusting. The Mississippian limestone is underlain conformably by fossiliferous Cambrian shale and a third quartzite exposure.

The pre-Cambrian granite southward disappears beneath a high alluvial fan which is now trenched by Santaquin Creek; but the main Cambrian quartzite body continues, and at its southernmost exposure rests again upon fossiliferous Mississippian limestone, which, as in the other instance, is surprisingly free from contortions and crushing. So far as the positions of the rocks are concerned, reverse or overthrust faulting seems the only interpretation; but the absence of disturbance in the overridden limestone is not easily explained.

At the mouth of Green Canyon, 8 miles south of Santaquin, an extremely brecciated and, so far as seen, non-fossiliferous limestone dips eastward beneath Cambrian quartzite, and here is the most convincing evidence of an overthrust, although time did not permit a thorough study of the immediate contact. A tunnel of the Excelsior Mining Company has been driven through the limestone into the quartzite, but the entrance to it was locked at the time of the writer's visit. No fossils were found in the underlying limestone, but the presence on the dump of fragments of a highly carbonaceous and finely pyritic bed, similar to two found elsewhere in the Mississippian of the southern Wasatch Mountains and of the Tintic district, gives a clue to the age of the limestone, and

accords with the structural relations in showing the fault to be an overthrust.

Block faults: A striking difference between the faults just described and the undoubted normal, or block, faults of the district

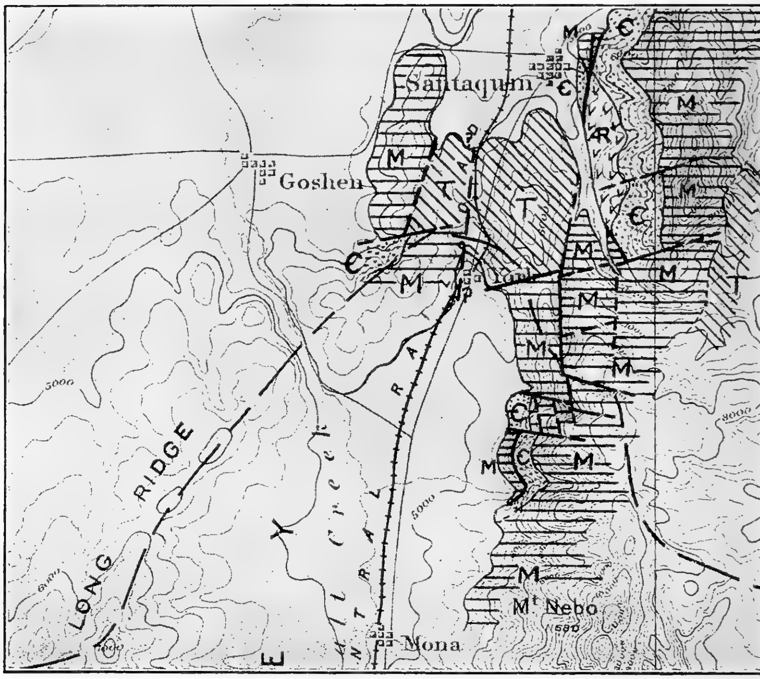

FIG. 4.—Geologic map of the Santaquin–Mount Nebo district showing overthrusts and block faults. ꟼR = pre-Cambrian granite, -€ = Cambrian quartzite; *M* = Mississippian and earlier limestones; *T* = Tertiary conglomerate and volcanics. Topographic base from the Manti sheet, United States Geological Survey.

is that the latter are marked by longitudinal and, to a less degree, by transverse valleys, whereas those interpreted as overthrusts appear unrelated to topography. From Santaquin southward nearly to Green Canyon (see Fig. 4) the western side of the range is composed of parallel ridges separated by remarkably straight N.-S. canyons. The strata on opposite sides of these canyons are quite discordant. For example, just north of Wash Canyon (6 miles south of Santaquin), the upper Mississippian "intercalated series"

with gentle easterly dip forms the low western ridge, and the pre-Mississippian limestones lie directly opposite on the west face of the main ridge. The "intercalated series" forms the crest of the main ridge, about 2,000 ft. above the western ridge. To the south across Wash Canyon, which follows a nearly E.-W. fault, the "intercalated series" is followed by Cambrian quartzite and limestones, and farther south a second E.-W. fault cuts off the Green Canyon overthrust. To the north, the "intercalated series" of the western ridge abruptly gives way, at another E.-W. fault, to the Eocene sediments and later volcanic breccia, which cover the low hills west of Santaquin Canyon, whereas the face of the main ridge east of the canyon is made up of the pre-Cambrian complex and lower Paleozoic strata, and the Tertiary beds are found only along its eastern base. The most obvious E.-W. (N. 70° E.) fault in the district is on the west side of the main ridge in a ravine just north of Santaquin Canyon, where the entire Cambrian quartzite and the overridden Mississippian limestone beneath it are cut off and followed on the south side by the lower (probably Cambrian) limestone beds.

It is of some interest to add that faulting later than the Tertiary volcanic flows was found by the writer last year in the East Tintic district and that this accords with the more convincing evidence in the Santaquin–Mount Nebo district, where the presence of faulted Eocene conglomerate and late or post-Eocene volcanic breccia places the time of the faulting and range uplifts not earlier than Miocene, thus confirming existing conclusions regarding the age of the basin ranges.

SUMMARY

In the Cottonwood district the "Ute" limestone and "Ogden" quartzite recognized by the Fortieth Parallel Survey are shown to be respectively parts of the Mississippian (and older) limestones and Cambrian quartzite.

The latter has overridden the former along an overthrust fault of easterly dip.

This overthrust is broken by at least two later reverse faults of westerly dip which were formed during the domal uplift induced by the granite intrusion.

Still later normal faults further complicate the structure.

The Mississippian limestone does not appear to be over 2,000 ft., and may be much less, above the Cambrian quartzite. The thickness of pre-Mississippian limestones is much less than in the northern Wasatch country, and greater than in the Uinta Mountains.

Cambrian quartzite, formerly called "Ogden (Devonian)," is exposed in three domal uplifts in the American Fork–Alpine district. Two of the domes are faulted, and the similarity of the structure to that in the Cottonwood district suggests that outlying bosses of the granite may underlie the domes.

Cambrian quartzite in the Provo district is exposed along two anticlines in line with each other, but oppositely unsymmetrical. A conglomerate bed in the quartzite contains impure limestone pebbles, indicating the existence of limestone of Cambrian or earlier age and an unconformity, presumably in the Lower Cambrian. Obscure exposures of dark limestone may represent a local bed intercalated in the quartzite, but the evidence at hand is not convincing.

In the Santaquin–Mount Nebo district the lowest exposed rocks are pre-Cambrian granite and schist, overlain unconformably by about 800 ft. of Cambrian quartzite, which is followed by 2,500 ft. of shale and limestone, in part or wholly Cambrian, and by Mississippian limestone. The upper Mississippian "intercalated series" east of Santaquin is overlain unconformably by Eocene conglomerate and volcanic breccia. To the west and southwest, the Eocene conglomerate rests upon pre-Mississippian limestone and Cambrian quartzite, proving the unconformity to have beveled off nearly the entire Paleozoic, as well as the Mesozoic, section. These latter occurrences mark approximately the western limit of Eocene sedimentation in central Utah.

Both overthrust and block faults are present in the Santaquin–Mount Nebo district. The former are for the most part obscure, but in each case are marked by Cambrian quartzite resting upon Mississippian limestone. The block faults are marked by N.-S. and E.-W. canyons, and are shown to be of post-Eocene age.

NEW SPECIES FROM THE SANTA LUCIA MOUNTAINS, CALIFORNIA, WITH A DISCUSSION OF THE JURASSIC AGE OF THE SLATES AT SLATE'S SPRINGS

CHARLES H. DAVIS

It is proposed in this paper to give very briefly the results of studies of the invertebrate fauna of the Franciscan slates at Slate's Springs, showing, first, that the fauna is older than the lower Knoxville, which itself is now being placed by many geologists in the Upper Jurassic (the slates, indeed, are much more faulted and metamorphosed than the sandstones of the Knoxville and dip under the Knoxville); secondly, that the fauna is not pre-Jurassic; and thirdly, that the molluscan fossils found at Slate's Springs, and named in this paper, are closely related to the described forms from the Middle Jurassic of Cook Inlet and the Alaska Peninsula, and from the Jurassic of Queen Charlotte Islands.

The locality under discussion is a narrow strip of seacoast extending from Point Sur southward to Slate's Springs, a distance of eighteen miles. About four miles north of the springs, collections of molluscan fossils and a few fragments of plants were made by Dr. H. W. Fairbanks[1] and Mr. F. M. Anderson in 1894. These collections are now in part in the Leland Stanford Junior University paleontological collection, and in part in the collection of the University of California.

It has been the work of the writer to describe and name what are judged to be new species from the above-mentioned collections, and to make note of those specimens which are too poor to serve for the identification of species. The *Sequoia fairbanksi*, described by Fontaine, is the only named fossil from this locality. The pecten from the San Luis formation of Fairbanks, and collected by him from a locality six miles north of Port Harford, San Luis Obispo County, is also described in this paper.

[1] "Geology of the Southern Coast Ranges," *Jour. Geol.*, VI (1898), 551–76.

The tellina here described was found among fossils characteristic of the Lower Temblor on the northern headwaters of San Antonio Creek, Monterey County.

SPECIES LISTED AND NAMED FROM SLATE'S SPRINGS

Pleuromya (?) *undulata* (n. sp.), L.S.J.U. FIG. 4.
Grammatodon inornatus Meek and Hayden.
Yoldia arata Whiteaves.
Nucula (*acila*) sp.
Inoceramus lucianus (n. sp.), L.S.J.U. FIG. 2.
Alaria fairbanksi (n. sp.), U. of C. FIG. 1.
Sequoia fairbanksi Fontaine.

FROM NEAR PORT HARFORD, SAN LUIS OBISPO COUNTY, CALIFORNIA

Pecten (*Camptonectes*) *harfordus* (n. sp.), L.S.J.U. FIGS. 3, 5, 6.

FROM UPPER SAN ANTONIO CREEK, MONTEREY COUNTY, CALIFORNIA

Tellina tenuistriata (n. sp.), L.S.J.U. FIG. 7.

DESCRIPTION OF SPECIES

Pleuromya (?) *undulata* (n. sp.). FIG. 4.

The specimens in the L.S.J.U. collection closely resemble *Pleuromya* (?) *carlottensis* Whiteaves,[1] but are somewhat larger. The specimen from Slate's Springs is strongly marked by broad concentric grooves, a characteristic not marked in the *P. concentrica* Whitfield and Hovey.[2] The right valve is distinctly convex in front and along the sides, becoming slightly concave at the posterior margin; outline ovate, short and rounded in front, produced and blunt posteriorly. The beaks are situated a distance of about one-fourth from the anterior end, apices wide but not acute. The hinge-line behind the umbones is almost straight, curving slightly upward at the posterior end; ventral margin broadly rounded. The surface is strongly and concentrically ribbed—the ribs separated by deep concave grooves.

Dimensions: Length, $3\frac{1}{2}$ inches; height, 2 inches; thickness of closed valves, $1\frac{1}{2}$ inches.

(?) *Grammatodon inornatus* Meek and Hayden.

One nearly perfect specimen of a left valve, several specimens showing middle and anterior end. The characters and dimensions agree with the description of *G. inornatus* by Whitfield.[3]

[1] Geol. Surv. Canada, *Mesozoic Fossils*, I, Pt. I (1896).

[2] *Am. Mus. Nat. Hist.*, XXII (1906), 389–402.

[3] *Geol. Black Hills of Dakota* (1880), p. 359, Pl. 5, Figs. 16–18.

Dimensions: Length, 18 mm.; height, 10 mm.; thickness of closed valves, 5 mm.

Cf. *Yoldia arata* Whiteaves, Geol. Surv. Canada, *Mesozoic Fossils*, I, Pt. III, p. 233, Pl. XXXI, Figs. 4 and 4*a*.

A single specimen, rather poor, but showing clearly the attenuate posterior end, elongation, strong concentric striations, and shallow concave slope of hinge from beaks to posterior end.

Dimensions: Length, 14 mm.; height, $6\frac{1}{2}$ mm.; thickness of closed valves, about 4 mm.

Nucula (*acila*) sp.

Shell small, nearly equilateral; subovate, moderately convex but depressed toward basal margin. Ribs divaricate from imaginary line running from beak to basal margin slightly anteriorly. Extreme length of shell from 7 to 15 mm. The wide range and common characteristics of the *Nucula* (*acila*) give it little determinative value.

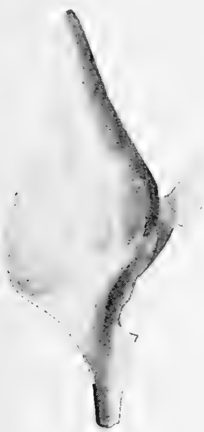

Fig. 1.—*Alaria fairbanksi*, natural size.

Fig. 2.—*Inoceramus lucianus*, one-half natural size.

Inoceramus lucianus (n. sp.), Fig. 2.

Several imperfect and broken specimens are in the L.S.J.U. collection. The one giving the best conception of the type is a cast of a left valve. The form is ovate or subquadrate, cardinal margin straight, basal margin semicircular. The beaks are rather low but pointed. The ribs on the type specimen are flattened by the pressure to which the rock has been subjected, but

other specimens show broad unequal concentric folds, often deep, as in the case of *I. elliotii* Gabb.

Height, $4\frac{1}{2}$ inches, is slightly greater than the length, $3\frac{3}{4}$ inches. This inoceramus is not of the catillus type.

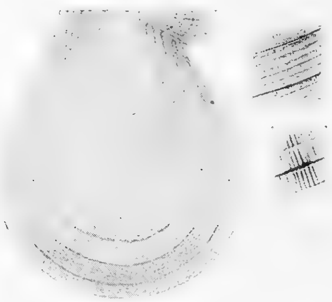

FIG. 3.—*Pecten* (*Camptonectes*) *harfordus*, twice natural size. (The details are four and eight times natural size.)

This species resembles *I. vancouverensis* in general size and outline, and in the direction of the hinge-line.

Alaria fairbanksi (n. sp.), FIG. 1.

A single imperfect specimen is in the paleontological collection of the University of California, and was collected by Dr. H. W. Fairbanks. The expanded outer lip and turreted form suggest the *Alaria*, a species of which occurs in the Vancouver Coal Measures.[1]

Dimensions: Height 55 mm.; thickness, about 20 mm.; extension of lip beyond shell proper, 15 (?) mm.

Sequoia fairbanksi Fontaine, *Mon. 48, U.S.G.S.* (1905), p. 78, Pl. XLV, FIGS. 9–11.

"From the Jurasso-Cretaceous of Slate's Springs, California. Collected in the rocks underlying the Knoxville group of the Lower Cretaceous. This

FIG. 4.—*Pleuromya undulata*, one-half natural size

plant is not unlike those from the Jurassic called by Heer, Elatides" (*op. cit.*).

Pecten (*Camptonectes*) *harfordus* (n. sp.), FIGS. 3, 5, 6.

[1] Cf. *Anchura stenoptera* Goldfuss (sp.) Whiteaves, Geol. Surv. Canada, *Mesozoic Fossils*, I, Pt. II, p. 123, Pl. 15.

A small thin pecten; form ovate, nearly smooth, and marked with fine almost microscopic groovings which radiate from the umbo and are deflected laterally from a median line on each valve. The shell is marked also by fine concentric lines, every fifth or sixth of which is more distinct. The anterior auricle is large; the anterior edge forms a right angle with the cardinal margin,

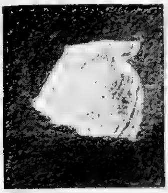

FIG. 5

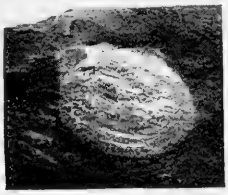

FIG. 6

FIGS. 5 AND 6.—*P. (Camp.) harfordus*, natural size

and rounds sharply into the deep byssal sinus. The left auricle is small and obliquely trunkated. The beaks are sharp and stop at the hinge-line.

This pecten is compared by Stanton[1] to *Pecten pedroanus*, but the latter differs from these specimens in having stronger radial markings especially on

FIG. 7.—*Tellina tenuistriata*, natural size

the auricles, and in general outline. It is like *P. bellistriatus* in its sculpture but is smaller; it has finer markings than *P. extenuatus* Meek.

Tellina tenuistriata (n. sp.), FIG. 7.

The specimens collected by the writer are from the Lower Temblor on the northern San Antonio headwaters, Monterey County, Cal. They are characterized by the fine concentric lines on both valves, and low beaks. The valves are rounded in front but are oblique and gaping behind; more or less rostrate.

Dimensions: Length, 2 inches; height, $\frac{7}{8}$ inch; thickness, $\frac{1}{2}$ inch.

[1] U.S.G.S., *San Luis Folio.*

CONCLUSIONS

First: The slate formation at Slate's Springs dips unconformably under the basal Knoxville beds, as described by Dr. H. W. Fairbanks.[1] The lowest Knoxville may be assigned to the Jurassic.

Second: The species from Slate's Springs are very similar, and in five instances out of seven are practically identical with described Jurassic forms. None of the species are unlike Jurassic forms. The *Alaria* shows that the beds are probably not pre-Jurassic.

Third: Five of the seven species listed from Slate's Springs are identical, or nearly identical with species described from the Queen Charlotte Islands. The Queen Charlotte Islands beds have been definitely correlated by Stanton[2] with the Enochkin formation of Alaska, which is called (Upper) Middle Jurassic.

Finally: The foregoing facts seem to place the Slate's Springs (Franciscan) beds not higher than the lower Upper Jurassic.

[1] "Geology of the Southern Coast Ranges," *Jour. Geol.*, VI (1898), 551–76.

[2] "Mesozoic Section on Cook Inlet and Alaska Peninsula," *Bull Geol. Soc. Am.*, XVI, 391–410.

GLACIAL POT-HOLES AT CROWN POINT, NEW YORK

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Glacial pot-holes have been described from various parts of the glaciated regions of North America and Europe. They occur singly or in groups, in positions unrelated to the beds of modern streams. Perhaps the best-known examples are in the famous Glacier Garden at Lucerne in Switzerland, where they are seen by many tourists every year. Even more remarkable than this most advertised occurrence is a small area on the Dalles of the St. Croix River near Taylor's Falls, Minn., described in detail by Upham (**31**). He says it is "unsurpassed by any other known locality in respect to the variety of forms and grouping, their great number and extraordinary irregularity of contour." In all, there occur within the area not fewer than 100, large and small.

The purpose of this note is to call attention to and describe a very fine specimen of glacial pot-hole that has been discovered recently at a place of commanding historic interest—Crown Point on Lake Champlain, a long promontory of horizontally bedded limestone jutting northward into the lake. Because of its great strategic importance this point was fortified by the French in 1731. Fort St. Frédéric, the stronghold they built, was captured and destroyed by the British under General Amherst in 1759. Immediately afterward, Amherst built the great star-shaped fortress with ramparts extending half a mile in circumference, whose ruins now attract thousands of visitors annually. In the summer of 1912, while these ruins were being explored and reinforced by the state government, the pot-hole here described was discovered.

Fig. 1 shows the pot-hole with the ruins of the soldiers' barracks and a portion of the ramparts in the background. It extends to a depth of 14 feet 7 inches into the topmost strata of the Chazy limestone formation. The aperture at the surface is an irregular oblong measuring 6 feet 4 inches by 9 feet 7 inches. The longer

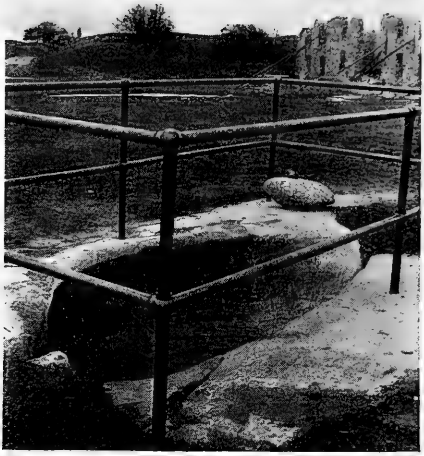

FIG. 1.—Glacial pot-hole at Fort Crown Point. Ruins of soldiers' barracks, with a bit of the encircling ramparts, and a glimpse of Lake Champlain in the background. (Copyright 1913 by E. E. Barker.)

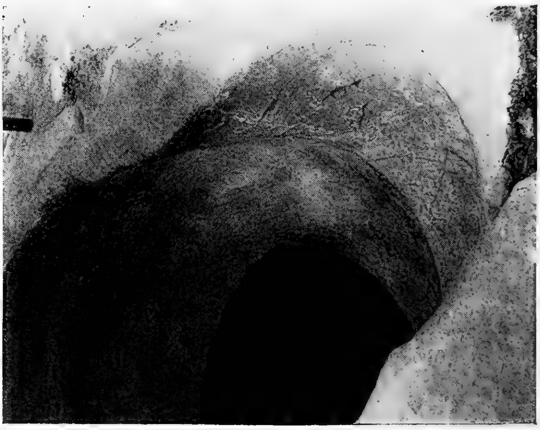

FIG. 2.—Glacial pot-hole, at Fort Crown Point. Looking in from above

axis coincides with a joint-plane. The pot-hole shows four stages of grinding, each deeper than the preceding, excentric to it, and somewhat larger in diameter (Fig. 2). The first and shallowest is farthest to the north. This might indicate that during the first stages of its formation the ice mass was moving southward. Its greatest diameter is 7 feet 4 inches, and is found just below the second shoulder. Beyond this the deep cylindric bore is attained. The inside surface is very smooth in places, but in part is marked with a low relief of ridges due to differential erosion of the harder and softer portions of the rock (Fig. 3). The pot-hole, when discovered, was filled with its original content of glacial débris intact. Many wagon loads of this material, consisting of large bowlders smoothly rounded, smaller cobblestones, with a filling of gravel and sand, were removed and piled in a cairn near by. They are mostly crystalline rocks, and are of great variety, representing nearly all of the formations found in the region to the north. The large bowlder that lay in the apex of the hole, together with two beautifully rounded smaller ones that lay on either side of it, has been preserved. The largest is shown just inside the railing in Figs. 1 and 3. These stones were evidently the active tools of the glacial torrent at the time when grinding ceased and the hole became clogged with the mass of débris with which it was filled. The surface of the surrounding rock is planed smooth and is scored with glacial striae.

Another glacial pot-hole occurs on Towner Hill, about six miles west from Lake Champlain, and about eight or ten miles southwest from the locality described above. This pot-hole was filled with ice when the photograph was taken, but it is said to be 8 or 10 feet deep (Fig. 4). At the surface of the ice its diameter measured 5 feet by 4 feet 4 inches. Its original depth must have been considerably greater, because it has suffered erosion since its formation that has truncated it obliquely to its perpendicular axis. The rear wall rises 5 feet 6 inches above the surface of the ice that filled it to the lowest portion of the rim at the time it was seen (Fig. 4). It is located half-way down the face of a cliff of hard gneiss at an altitude of about 1,260 feet according to the U.S. Geological Survey sheet (Paradox Lake Quadrangle, N.Y.). The

FIG. 3.—Glacial pot-hole at Fort Crown Point, showing irregular aperture, ridged inner surface, and the principal grinding-stone.

FIG. 4.—Glacial pot-hole on Towner Hill, Crown Point, N.Y.

rim is smoothed and rounded off, and it has unmistakably undergone great erosion and weathering since it was bored.

At the foot of the cliff is the remnant of a still larger pot-hole that now forms a shallow niche in the face of the cliff, and comprises the arcs of two intersecting circles with a combined diameter of 12 to 15 feet for the original pot-hole. The diameter of the smaller arc is computed to be 6.12 feet. Its depth is unknown, as it has never been cleared of the débris that fills it.

Upham (**31**) describes a pot-hole in the Interstate Park at Taylor's Falls in every way similar to this latter one. He suggests the hypothesis that it was formed partly in rock and partly in ice, and that when the ice melted away it was left in the imperfect form seen at present. The pot-hole described here, however, because of its proximity to another that shows unmistakable evidence of erosion, would seem to favor the hypothesis that it was bored in solid rock, and that, subsequently, the greater portion of it had been eroded away. Both pot-holes occur nearly at the top of a mountain, and are far from any stream bed. Their partial demolition after their formation supports Upham's hypothesis that such pot-holes were formed during the early stages of the ice-sheet; but they can be equally well explained by the advance of a later ice invasion.

March 17, 1913.

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REVIEWS

C. DOELTER, *Handbuch der Mineralchemie* Band I. (Dresden und Leipzig: Theodor Steinkopff. M. 45.)

The need of a standard work of reference dealing more particularly with the advances made during the last twenty years in our knowledge of mineral statics has been in recent years a very pressing one. The works of Vogt, Tscherwinsky, Doelter, Van Hise, Harker, Elsden, and Clarke have each taken up certain aspects of the subjects, but exhaustive treatment was impossible within the limits imposed. The appearance of the first volume of Doelter's *Handbuch* is, however, sufficient surety that such a work is now to be provided. But it is today no longer possible for one writer to cover the whole field of mineral chemistry, and it has been found desirable in the work under consideration to obtain the services of some 58 contributors, in order especially to insure that the four volumes shall appear within a reasonably short space of time, and consequently at one particular stage in the development of the subject. While the plan leads to a certain amount of overlapping—not in itself necessarily an evil—it has the great advantage that no part of the subject is left untouched, and that every aspect is handled by an authority in that particular field. And in this connection one cannot fail to remark on the fortunate position in which the editor was placed in that he could draw so fully on the resources of the Vienna school.

In two aspects in particular the work represents a marked advance on the older treatises of Rammelsberg and Hintze. The technical application of minerals and mineral materials receives full treatment. Thus in the volume already issued articles appear on the industrial uses of magnesite, on cement, glass, glazes, and enamels. These subjects are discussed in their physicochemical and mineralogical bearing, and the two articles on cement and Zschimmer's exhaustive paper on glass form valuable statements of the results of recent investigations on subjects which are intimately connected with the sciences of mineralogy and petrology. But the dominant line of progress at the present time is the elucidation, largely from the experimental standpoint, of the genesis and stability conditions of minerals that play an important rôle as rock-formers, no matter whether they form from silicate fusion or from aqueous solution. The name of the editor has long been associated with

this line of investigation, and it is from this standpoint in particular that the *Handbuch* will be considered the authoritative work of reference. Consequently it is not merely a treatise on mineral chemistry. It cannot fail to deal as well with the most fundamental problems of petrogenesis.

Some difficulty has been experienced in arriving at an entirely satisfactory arrangement of the material. The older classification of Groth, in which the elements that occur as minerals are first disposed of, has been discarded, and an arrangement has been adopted which is based on, but does not follow in complete detail, the periodic classification of the elements. Thus in the volume now before us carbon and its compounds are first dealt with, and the treatment of silicon and of some of the general aspects of the silicates then follows. Out of some 150 articles it is perhaps invidious to single out any particular cases, as the selection inevitably depends materially on the subjects in which the reviewer is specially interested. Two of the features of the first volume to which the writer has given more careful attention are the articles on the carbonates by Leitmann, and Doelter's paper on silicate melts. Leitmann in a long series of articles has dealt with the naturally occurring anhydrous carbonates, and has handled a literature of enormous proportions with marked judgment and reserve. Particularly valuable are the discussions on synthesis and processes of formation in nature, and the physico-chemical treatment of the solubilities. It is part of the plan of the *Handbuch* to introduce a broad division of the minerals by an article dealing with the whole or part of the field from the comparative standpoint: and Linck's suggestive article on the carbonates of lime, iron, and magnesia summarizes the work of the Jena school on the stability conditions of these compounds as they occur in nature.

Doelter's contributions to this volume deal with the formation of graphite, the carbonates, phosgenite, silicon, the synthesis of the silicates, and silicate fusions. The last is an article of almost 200 pages, which reviews the whole field and emphasizes the lines of investigation at present being pursued. On some points in this paper there will be a decided difference of opinion. While it cannot be doubted that Doelter's insistence on the registration of two temperatures on the fusion curve gives a much-needed emphasis to the fact that silicates react with remarkable slowness, the methods on which he has chiefly relied can hardly be considered to have been so fruitful in the interpretation of two-component systems as the methods of thermal analysis applied by Tammann and his school to the alloys and later to the silicates, or as used

in somewhat different form with such marked success in the Carnegie Institute of Washington. One cannot but feel that Doelter's attitude with reference to some of the work of the American school is unfortunate. Of particular interest, however, are the sections on electrical conductivity, on specific heat and latent heat of fusion, and on the relation of the whole subject to rock crystallization and differentiation. While certain parts of the article are to be found in Doelter's earlier books, it is by far the most complete and valuable résumé of the subject of silicate fusions that we yet possess.

The services of Dittrich have been secured to deal with methods of analysis of the various classes of minerals. Vogt contributes an article on slags, and treats the subject rather more from the standpoint of the metallurgist than in his previous works with which petrologists are acquainted. It need only be added that the publishers seem to have fully realized the value of the *Handbuch*, and have spared no pains to make it a most attractive addition to a reference library. May the other three volumes very soon find their place beside this one on the library shelves.

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An Introduction to the Mathematical Theory of Heat Conduction, with Engineering and Geological Applications. By L. R. INGERSOLL and O. J. ZOBEL. Boston: Ginn & Co., 1913. Pp. 171, 24 figs.

Although primarily intended for students of physics, this textbook contains, as its subtitle would suggest, a certain amount of material that has an important bearing on geological problems, especially those that have to do with the transfer of heat. In chap. vii, on "The Linear Flow of Heat," some of the sections bearing on geology are: thawing of frozen soil, cooling of lava under water, cooling of the earth with and without radioactive considerations, and estimates of age, heat sources, temperatures in decomposing granite. Chap. viii, "The Flow of Heat in More than One Dimension," treats the cooling of a laccolith and the cooling of a sphere by radiation.

The conclusions on the nature and rate of progress of a heat wave traveling from a laccolith into limestone throw interesting light on the conditions of the contact metamorphism of limestone and the development of ores at such points. The slow advance of the heat wave, allowing as it does a difference of temperature of about 50° C. at points 200 meters on either side of the contact, at the end of 10,000 years, must be a

very important factor controlling the work of underground waters. Again, this same process demands, first the development of a compressional condition in the limestone, followed later by a period of tensional stresses as the rock cools. Accordingly, the compressional phase advances like a wave normal into the limestone, followed by a tensional phase which tends to produce fissures. This accords with the facts observable at limestone contacts. Chap. ix deals with the conditions of the formation of ice.

The handling of the problems in each case is highly mathematical as the title of the book would suggest, but the results obtained may be somewhat readily applied to many concrete cases in geological science.

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THE GENERAL PRINCIPLES UNDERLYING METAMORPHIC PROCESSES

JOHN JOHNSTON AND PAUL NIGGLI
Geophysical Laboratory, Carnegie Institution of Washington

CONTENTS

PART I

PART I

INTRODUCTION

The term metamorphism in its widest sense includes all the alterations which occur in solid rock; it therefore comprises those processes which change the composition (mineral or chemical), structure, and texture of rocks after they have been formed, no matter what may have been their origin—by solidification from magma, consolidation of chemical precipitates, or mechanical deposit. But we, following Grubenmann, shall limit this somewhat and consider as typical cases of metamorphism only those in which the effects produced by the alterations determine completely the character of the rock mass.

An essential characteristic of metamorphic alterations is that the rock *as a whole* remain solid during the process. This condition does not hold whenever the original rock has at any instant been wholly melted; such a case is merely a solidification under special conditions from a magma, and the rock formed in this way is indistinguishable from an eruptive rock. When once a rock has been completely melted, we can say nothing of its particular history previous to that time; in especial we cannot know whether any of the components of the rock have existed previously as solids.

The crystalloblastic structure[1] described by F. Becke and by U. Grubenmann could not be accounted for if the new-formed rock had been formed out of a completely fluid medium, but is easily correlated with all the other properties of rocks formed by metamorphism if we regard the change to be the result of a process of melting (or of solution) which at any instant is local and partial only.

Metamorphism of rocks is effected by change of temperature, of uniform pressure, of stress, and of concentration; it occurs whenever the original components become unstable by reason of the changed external conditions, provided always that the velocity of reaction is appreciable. The above are the important factors in determining any chemical equilibrium, so that in the study of metamorphic processes it is necessary only to apply well-known physico-chemical principles to these special, and in general complicated, systems; indeed a beginning in this direction has already been made, in the well-known work of Van Hise, Becke, Grubenmann, and V. M. Goldschmidt.

The opinion has been held that physico-chemical principles are incompetent to account completely for the phenomena of metamorphism, for the reason that the system is in many cases not in a state of true equilibrium, either during the process of metamorphism or after alterations of the system have practically ceased. This lack of stable equilibrium is due to the small rate of reaction under the particular conditions, and hence is part of the large physico-chemical problem of the relation between rate of reaction and the general properties of the system or of its components.

To grasp the general effects produced by the various agents concerned in metamorphic processes is easy, even though quantitative data are still lacking; but the application of these principles to particular cases demands a clear and well-defined knowledge of

[1] It is to be remarked that the words *Textur* and *Struktur* have a signification in German which is different from the meaning usually attached to their equivalents in English. According to contemporary German usage, which is based on the definitions given by Becke and Grubenmann, *Textur* is arrangement in space, while *Struktur* is used to express genetic relationship. Hence crystalloblastic structure has nothing to do with textural relationships such as are observed in flow cleavage; for instance, the structure of the massive eclogites is typically crystalloblastic.

their effectiveness and limitations, in order that effects may not be attributed to causes which are incompetent to account for them. The present paper is an endeavor to discuss the validity, the limitations, and the relative importance of the general principles involved; our aim has been, in bringing them definitely to the attention of geologists, to show that it is no simple matter to apply these principles, simple in themselves, to the very complicated systems encountered under geological conditions, and that very careful reasoning is required if correct conclusions are to be reached. We wish to emphasize especially the distinction which must be made between uniform pressure and non-uniform compression or stress. The importance of uniform pressure, and the magnitude of the effects producible by it, have frequently been overestimated, while on the other hand insufficient account has been taken of the comparatively much greater effects which may result from the action of non-uniform compression.

We shall not go into the various kinds of metamorphism—regional-, contact-, dynamo-metamorphism, etc., for in all cases the final effect is determined by the same factors, namely, temperature, pressure, stress, chemical composition,[1] and speed of reaction. One factor may be predominant in one kind of metamorphic process, another factor in a second; but by combination of the above factors, all of the observed effects attributed to metamorphism may be accounted for.

In the following pages we present a discussion of the most important general principles involved, especially of those principles which have not always been applied correctly by those who have made use of them. We have, for the sake of clearness, divided up the subject-matter under a number of headings, to which we have, however, deemed it inadvisable to adhere strictly throughout; these are intended to be read only in the light of the general context, as it was impracticable to insert always the qualifying phrases required to render the statements strictly accurate. Moreover, this paper does not pretend to completeness, either from the chemical or from the petrologic side; it aims to treat the various

[1] By this is to be understood the gross chemical composition of the whole system at the period of metamorphism, and not the chemical composition of the rock-mass now.

topics only in so far as they are important in regard to metamorphic processes.[1]

Furthermore, the references to previous work are in no wise to be understood as a bibliography of the subject; they are given merely as illustrations, or expansions, of the ideas in the text, and have been chosen from the work with which the writers happen to be most familiar.

In pursuance of this plan, we give first a brief discussion of the general effects of temperature and pressure, followed by sections dealing with the general behavior of systems when exposed to (1) uniform pressure, (2) non-uniform compression or stress. Chemical composition is always specific and characteristic of the particular system; therefore it cannot be discussed in a general way, but must be ascertained by experiment for each system. A similar remark applies to rate of reaction.

EFFECTS OF TEMPERATURE AND PRESSURE ON SYSTEMS SOLID-SOLID[2]

General considerations.—A very large number of all crystalline substances exist in more than one crystalline form;[3] thus silica appears in at least seven distinct forms, sulphur in at least four solid forms, and so on. And it is a matter of common knowledge that further and more extended investigation always swells the list of polymorphic substances; so that it would appear as if poly-

[1] For fuller information on the chemical topics the reader is referred to textbooks of theoretical chemistry: the more elementary books of Walker, *Introduction to Physical Chemistry* (Macmillan), or Senter, *Outlines of Physical Chemistry*, the larger general works of Ostwald, *Allgemeine Chemie*, or Nernst, *Theoretische Chemie*, or the more special books, such as Roozeboom's *Heterogene Gleichgewichte* or those in the series edited by Ramsay and published by Longmans; on the petrologic side, to books such as Harker, *Natural History of Igneous Rocks*, Elsden, *Principles of Chemical Geology*, and especially to Grubenmann, *Die kristallinen Schiefer*. Doelter's new *Handbuch der Mineralchemie* is a collection of observations, rather than a critical discussion of the subject, and it is not entirely free from errors of interpretation.

[2] Throughout this paper the term solid is used to designate *crystalline* material, as distinct from amorphous material (glasses); the latter are merely subcooled liquids, which differ from ordinary liquids only in that their viscosity is almost immeasurably greater.

[3] A fairly complete list of the instances known up to 1893 will be found in Arzruni, *Physikalische Chemie der Krystalle* (Braunschweig, 1893).

morphism were the rule rather than the exception, at least with inorganic substances, especially with those of geologic interest. Let us consider what happens when we heat very slowly a substance capable of existing in more than one polymorphic form; and for the sake of simplicity, let us assume that the substance exists only in two forms, which we may designate as α and β. This assumption of only two forms really implies no limitation of generality, for even with a substance which may be obtained in more than two forms we are dealing with only two of them in the neighborhood of any single transformation temperature. Now as we slowly heat the α form, we find a slow but continuous change in its physical properties:[1] e.g., in density, refringence, and (in general) axial ratios; this gradual change goes on, until finally we observe a much more marked change of properties—which may take place either at a definite temperature or within a small range[2] of temperature—denoting that the transformation into the β form has been effected. Further heating now is accompanied anew by a gradual change of properties, a change characteristic of the β form and bearing no necessary relation to the corresponding changes shown by the α form.

If now we cool again through the transformation temperature, the α form may or may not appear. Failure to reappear may be due to one of two causes: (1) that *under the particular conditions* the rate of transformation of β into α is extremely slow, or, in other words, the attainment of equilibrium requires a long time; (2) that the equilibrium between β and α is such that β is the stable form throughout the temperature range in question; consequently α can then not appear no matter how much time is allowed.

Transformations belonging to the first class—that is, where equilibrium can be attained from either side—are known as *enantiotropic;* changes which are irreversible are called *monotropic.* We shall discuss these separately; but before doing so, we wish to direct attention to a point which, though important, is often lost sight of.

[1] A much more profound, though continuous, change is of course possible, e.g., on heating zeolites and other hydrous minerals (see F. Rinne, *Fortschritte Min.*, 1913 (3), 159–83).

[2] At least, if the rate of heating has been small.

Importance of the rate of transformation.—The point in question is that the factor which determines the actual experimental result may be the rate at which equilibrium is established under the particular conditions. We must therefore always ascertain whether the observed result is, or is not, due to a laziness—as opposed to an inability—to react; in other words, we must distinguish carefully between cases of true and *apparent*, or false, equilibrium. Lack of care in this matter may lead us to consider a transformation to be monotropic or a given form to be stable under conditions where it really is metastable, its persistence in either case being merely the result of a slow rate of transformation.

As an illustration, take the system represented by the scheme $2H_2+O_2 \leftrightarrows 2H_2O$, a system which has been so thoroughly investigated[1] that we know the conditions of equilibrium at all temperatures up to 2,600°. These conditions are such that at all temperatures below 1,000°, the pressures of oxygen and hydrogen which can exist in real equilibrium with water are infinitesimally small;[2] hence, if *real* equilibrium obtained, it would be altogether impossible to preserve in presence of water an appreciable amount of a mixture of oxygen and hydrogen. In other words, this system is, theoretically, absolutely unstable; *practically*, however, hydrogen and oxygen may be left in contact together with water for an unlimited time at ordinary temperatures, and still show no signs of reaction, which begins only at fairly high temperatures, i.e., when its velocity becomes appreciable.

This case is instructive also in showing that there is no necessary parallelism whatever between the "affinity" of two substances for one another (which is measured by the change of free energy accompanying a reaction) and the rate of reaction under any particular conditions. Thus the above reaction does not go (except at high temperatures), although the energy change accompanying it is one of the largest known; on the other hand, many reactions with comparatively feeble energy changes go quite readily. Moreover,

[1] See Nernst, *Theoretische Chemie;* Bjerrum, *Z. physik. Chem.*, LXXIX (1912).

[2] Thus the extent of dissociation is of the order of 10^{-25} per cent at 25°, 10^{-5} per cent at 700°, and does not reach a magnitude which is directly measurable until about 1,200°, where it is about 0.02 per cent.

if there were a definite connection between heat of reaction and rate of reaction, the existence of endothermic compounds would appear to be highly improbable, if not impossible.[1]

The rate of reaction varies enormously with the temperature, in general doubling for a rise of 10°. A rise of 100° therefore causes a reaction to go about one thousand times faster, while its speed is increased about a million times when the temperature is raised about 200°. In accordance with this we find that the rate of transformation of one crystal form into another tends to be greater the higher the temperature at which the transformation takes place.[2] There is very little direct evidence with regard to the effect of pressure on the rate of reaction (as distinguished from its effect on the position of equilibrium); such as there is indicates that it has little, if any, effect.[3] In any case it is a safe assertion that the effect of pressure on the rate is absolutely negligible as compared with the enormous acceleration produced by change of temperature.

The rate of a reaction is quite generally much affected by the presence of certain specific substances; thus, palladium black brings about the union of oxygen with hydrogen around 100°. Such substances affect only the rate at which equilibrium is established, but are usually understood to be without influence on the position of equilibrium; they are commonly grouped together, for convenience, as *catalysts*—a term used to conceal our present lack of knowledge of the mode of action of the majority of them. In some cases it is known that the catalytic agent acts merely as a solvent, hence producing its characteristic effect; as examples, we

[1] There is a relation between the explosibility of such metastable gaseous mixtures and the heat change accompanying their reaction.

[2] There is of course in principle absolutely no difference between a reaction and a transformation, the latter including the processes of fusion, sublimation, and vaporization as well as the change from one crystal form to another; all are amenable to the same thermodynamical reasoning. The only differences are in the number of components, which cause corresponding differences in the equations expressing the relations quantitatively, the qualitative relations being deducible from the phase rule.

[3] Doelter (*Handbuch Mineralchemie,* I [1912], 604) estimates the influence of pressure on speed of crystallization to be great for the reason that crystallization is hastened by shaking or knocking; this inference, however, is incorrect, because he fails to distinguish between uniform and non-uniform pressure, attributing to the former effects which could only be produced by the latter.

have the use of sodium tungstate in accelerating the reciprocal transformations of the forms of silica, and the effect of water on mixtures of calcite and aragonite—and still more, of water containing carbon dioxide, in which the solubility is greater—in converting aragonite into calcite at 100° or lower, whereas in the dry state the rate of conversion is not appreciable until temperatures around 400°. The action of many catalytic agents is known to depend upon the formation of unstable intermediate products, but for a very large number the mechanism of their action is still unknown.

It is essential, then, that we bear in mind, on the one hand, the distinction between the theoretical state of equilibrium and, on the other hand, that actually attained under a given set of conditions together with its dependence upon the rate of reaction under those conditions. Indeed, we may say that in a very large number of cases the reaction velocity is the decisive factor in determining the final state, though of course the *direction* in which the reaction proceeds is determined by the energy relations, under the specific conditions of the experiment, of the various substances involved.

Enantiotropic transformations.—Enantiotropic transformations are those in which equilibrium can be attained from either side, and mark the transition of one perfectly stable form into another. The rate of transformation varies enormously from one substance to another, or for a single substance even from one transformation to another. As an illustration take the substance silica:[1] quartz, when heated to 575° goes over quite sharply into another form (β-quartz), but both its transformation to tridymite at or near the inversion point (870°), and the change of the latter to cristobalite at 1,470°, proceed very slowly. There is as yet no means of prognosticating the rate of transformation; except that one may hazard the general statement that, for any single substance, those inversions which are accompanied by the slightest changes of crystal form tend to proceed most rapidly, while the rate of transformation is small wherever the change of crystal form is large.

The temperature at which an enantiotropic transformation takes place is always perfectly definite, although it may appear to lack definiteness when equilibrium is established only slowly; it is

[1] C. N. Fenner, *Jour. Wash. Acad. Sci.*, II (1912), 471.

affected by the presence of impurities if the system is homogeneous, and by uniform pressure, this effect being altogether analogous to that observed with melting-points, and subject to the same thermodynamical formulation. So far as we are aware, no experimental study has been made of the influence of uniform pressure on the transition point of any system solid-solid of direct geological interest;[1] but if the appropriate data were known, this effect could be calculated with sufficient exactness from the equation

$$\frac{\Delta T_2}{\Delta P_2}=\frac{T(V_\beta-V_\alpha)}{41\cdot30\,Q}$$

whereby ΔT_2, the change of transition point produced by a change of pressure, ΔP_2 (reckoned in atmospheres), is expressed in terms of Q, the heat of transformation in calories per gram, T, the temperature of transformation at 1 atm., and V_α and V_β, the respective volumes (in c.c.) of 1 gram of substance before and after the transition at T. Unfortunately, however, the requisite data, especially the values of Q, are known in very few instances, and are altogether lacking for the inversions of geologic significance. It is perfectly obvious, therefore, that one may just as well guess the final result as calculate it from the formula, using *assumed* values of the constants involved.

In passing, it may be observed that there is no general parallelism between Q and the volume change $\Delta V=(V_\beta-V_\alpha)$. Thus potassium bichromate has an inversion point at about 240°, accompanied by a large volume change but by only an inappreciable heat effect.[2] On the other hand, during the inversion of cuprous sulphide at 79° considerable heat is evolved, and yet ΔV is only about 0.0001 c.c. per gram.[3]

[1] The effect of pressure on the equilibrium between the various solid forms of water has been investigated by Bridgman (*Proc. Am. Acad.*, XLVII [1912], 441; *Z. anorg. Chem.*, LXXVII [1912], 377); the case of sulphur, which was studied by Tammann (*Krystallisieren und Schmelzen*), is discussed in most textbooks. Some observations have also been made on the effect of pressure on liquid-crystalline transformations, which, however, resemble melting-points much more than they resemble any transitions of geologic interest.

[2] Mitscherlich, *Pogg. Ann.*, XXVIII (1833), 120.

[3] Hittorf, *ibid.*, LXXXIV (1851), 1; Tammann, *Krystallisieren und Schmelzen* (Leipzig, 1903), p. 40.

Transformation points solid-solid are presumably not affected by unequal pressure,[1] which is equivalent to a shearing stress; in this respect they are unlike melting-points. For where melting occurs, the pressure will be greater on the solid than on the liquid phase, owing to the flowing-away of the latter; at transformation points, on the other hand, where both are solid phases, they must be equally subject to the pressure, and therefore the comparatively *large* effects produced by unequal pressure on melting-points will be absent at inversion points.[2] Nevertheless it is entirely probable that persistent unequal pressure (differential stress) might increase the rate of inversion $\alpha \rightarrow \beta$, the latter being the form normally stable at high temperatures; for it is conceivable that unequal pressure in sufficient amount should lower the melting-point of the α-form to such a point that an actual progressive melting[3] of α takes place followed by a crystallization to the β-form, if that were the form stable under these particular conditions.

To illustrate, there are a number of metastable forms (for example, yellow HgI_2 at temperatures below *ca.* 120°, yellow PbO below *ca.* 550°) which can be changed into the corresponding stable forms merely by scratching or rubbing in a mortar.[4] This mode of action of unequal pressure recalls that of catalytic agents, and may be used to aid in accounting for the fact that metamorphic processes occurred easily in those regions which have been exposed to stress.

Enantiotropic transformation of mix-crystals.—We must call special attention to a circumstance which is often neglected although it is of great importance in petrogenetic systems: namely, that the temperature of an enantiotropic inversion has a single definite value only when both the forms involved in the equilibrium are

[1] The idea of "unequal pressure" and its consequences are discussed more fully in a later paragraph.

[2] Nevertheless, there might be some comparatively slight effect; for if the process of transition occurred through a melting (as is outlined in the next sentence in the text), the *difference* between the effects of such unequal pressure on the melting-points of the α and β forms would be its net effect in changing the temperature of inversion.

[3] By this it is not meant that the whole of α should at any instant be melted; see a later paragraph.

[4] It is of course possible that the slight local rise of temperature produced by grinding also plays a subsidiary role in this process.

simple phases and not mix-crystals (solid solutions). This same reservation holds for melting-temperatures, and is there well known. When a mix-crystal of the α-form undergoes enantiotropic change into a mix-crystal of the β-form, there is in general a *temperature-interval* in which the α and β forms may coexist in real equilibrium. As the temperature changes within this region, there is a continuous change in the composition of the mix-crystals, which are in equilibrium with one another, precisely as in the melting of mix-crystals or the distillation of binary liquid mixtures, and for the same reason.[1] The position of this temperature interval is dependent upon the composition of the possible solid solutions, and may be displaced considerably if the corresponding inversion temperatures of the end-members of the series of mix-crystals are far apart.

As an illustration consider the system HgI_2-$HgBr_2$ and its inversion tetragonal→orthorhombic.[2] At 127° red tetragonal HgI_2 changes into yellow orthorhombic HgI_2; $HgBr_2$ is known only as the white orthorhombic form, so that the inversion point of the tetragonal form, if it exist at all, must be at a low temperature. From melts containing both components there separate out a continuous series of orthorhombic yellowish-white mix-crystals ($n\ HgI_2 \cdot m\ HgBr_2$); but the mix-crystals containing little $HgBr_2$ invert at low temperatures into a tetragonal modification. The temperature at which this inversion begins is lower the richer the mix-crystals are in $HgBr_2$; hence the reason that mixtures rich in $HgBr_2$ exhibit no inversion point is in all probability that the velocity of transformation at the equilibrium temperature—which then must be below 0°—is inappreciable. When a mix-crystal of the composition 9.5 mol. per cent $HgBr_2$, 90.5 mol. per cent HgI_2, is cooled slowly (care being taken that the rate of transformation is sufficiently great), it begins about 80° to change to the tetragonal form, producing tetragonal crystals approximately of the composition 2.6 mol. per cent $HgBr_2$, 97.4 mol. per cent HgI_2. Further

[1] See papers by N. L. Bowen, *Am. Jour. Sci.*, XXXIII (1912), 561; "The Melting Phenomena of the Plagioclase Feldspars," *ibid.*, XXXV (1913), 577.

[2] W. Reinders, *Z. physik. Chem.*, XXXII (1900), 494; P. Niggli, *Z. anorg. Chem.*, LXXV (1912), 161.

cooling is accompanied by a progressive change of the orthorhombic into the tetragonal form with a corresponding alteration of composition of the mixtures in both modifications, until finally at about $-20°$ the system is completely transformed into tetragonal mix-crystals of the composition 9.5 mol. per cent $HgBr_2$, 90.5 mol. per cent HgI_2. Thus at temperatures between $+80°$ and $-20°$ (under ordinary pressure) mix-crystals of the above composition represent an equilibrium between two modifications of different composition, either of which is completely stable in presence of the other.

Now among the minerals of geologic importance there are many which are to be considered as solid solutions; from the foregoing, therefore, one must speak not of the inversion *temperature* of any such mineral which exists in more than one form, but only of the inversion interval. For instance, if the relation between augite and hornblende should prove to be enantiotropic (at present the nature of their relation is unknown), they could coexist in *true equilibrium* throughout a range of temperatures. It would therefore be incorrect to speak of a definite temperature, or a definite pressure, of transformation of these important minerals.

Furthermore, the modifications which coexist in equilibrium under any particular set of conditions will not have the same chemical composition. As a matter of fact, such differences have been observed in gabbros from Katéchersky by L. Duparc,[1] who gives the following analyses:

	Augite	Amphibole
SiO_2	50.91	43.34
Al_2O_3	2.64	12.60
Fe_2O_3	.....	10.44
FeO	10.07	7.92
MnO	0.41	.....
CaO	23.33	12.91
MgO	13.30	12.52
K_2O	Not determined	0.24
Na_2O	Not determined	1.90
	100.66	101.87

[1] *Bull. soc. franc. min.*, XXXI (1908), 50. Analogous observations have been made by L. J. Wild, *Trans. New Zealand Inst.*, XLIV (1912), 333; also by J. B. Harrington, *Geology of Canada* (1879), p. 21.

The augites were considerably "uralitized" (transformed into fibrous hornblende, appearing as pseudomorphs of the augite), the process being accompanied by a marked change of composition. This interpretation of the process presupposes equilibrium conditions; but whether equilibrium conditions obtained or not, this example may serve to point out the possibility of the actual occurrence of such differences.

Closely related to the phenomena of transformation of mix-crystals is the phenomenon of allotropy, according to the latest views, which so far are the only views which aid us materially in correlating this property with other properties of the substance.

The phenomenon of allotropy.—It is well known that wherever a substance exhibits polymorphism, its various allotropic modifications may be obtained from a solution or fusion merely by varying the conditions of crystallization (e.g., rate of cooling, concentration of solvent). On this fact as foundation, a theory of allotropy has been developed by Smits,[1] the basic idea of which is that the different modifications are in reality all present in equilibrium with one another in the solution, the appearance of any one form in the solid state being determined by the conditions of this internal equilibrium, the position of which in turn is affected specifically by the solvent medium.

Let us consider, for the sake of simplicity of statement, that no foreign solvent is present, that the liquid phase is a melt of the pure substance. Such a liquid phase, which hitherto has been generally supposed to be unary (containing only a single molecular species), is considered by Smits to be pseudo-unary; that is, it contains two (or more) pseudo-components in mutual equilibrium. As a necessary consequence of the internal equilibrium in the liquid phase it follows that there is equilibrium in the solid phase between the same pseudo-components; the position of this equilibrium is, of course, not identical with that of the equilibrium in the liquid phase (just as in the case of mix-crystals). In other words, when an apparently unary liquid solidifies, even although the cooling goes on in such a way that equilibrium between the pseudo-components obtains continuously, the solid phase separating out is not a pure pseudo-component but is itself a pseudo-unary system in internal equilib-

[1] A. Smits, *Z. physik. Chem.*, LXXVI (1911), 421, and later papers in 1912 and 1913, especially *ibid.*, LXXXII (1913), 657.

rium and therefore is a mix-crystal. The solid forms actually known to us are not the pure pseudo-components themselves, but are solid phases in an equilibrium which is displaced by external circumstances toward one side or the other. The displacement of equilibrium in the solid phase produced by change of external conditions may proceed until unmixing supervenes, i.e., until an inversion point is reached.

This theory has already justified itself as a working hypothesis at least; it has enabled Smits to co-ordinate certain phenomena and hence in part to predict the behavior of certain systems. This success indicates the great probability of the existence of internal equilibria, and in this respect it is in complete harmony with a number of other lines of evidence. It leads us to look upon a single crystal, not as a simple body, but as a more or less complicated configuration the behavior of which depends on the state of equilibrium within the crystal.

Moreover, it possesses a great advantage as compared with the old point of view in that it affords a clue to the problem of the apparently arbitrary appearance of metastable modifications. For if we know the diagram of such a pseudo-unary system—that is, if we know the equilibrium lines in both the liquid and the solid phase as well as the mix-crystal and liquidus curves—we can foretell which factors will promote, or hinder, the formation of a given metastable product. For instance, if the speed of attainment of equilibrium is small and the temperature change is rapid, the equilibrium will not have time to adjust itself to the changing conditions; unmixing therefore will occur at a composition (with respect to the pseudo-components) and at a temperature which differ from those corresponding to continuous real equilibrium—in other words, the resultant products in the two cases are different. The position of the various equilibrium lines and the rates at which the various equilibria are established under the particular conditions are, in short, the factors that determine which product actually appears. Hitherto the only aid in the prediction of what would appear has been that derivable from the so-called Ostwald rule,[1] a

[1] The rule, as stated by Ostwald, is: In all reactions the most stable state is not straightway reached, but the next less stable or that state which is the least stable of the possible states. It may be observed that this alternative mode of statement insures the validity of the rule in a large number of cases.

rule to which there are very many exceptions. From the above we see that the rule—in spite of its breadth—will not be generally applicable; for if it were, it would imply limitation of the type of possible configuration of the diagram of state, whereas there is no reason to believe that such limitations exist.

From this point of view also we can see how the phenomena of monotropy and of allotropy are related. Whether one or the other of these phenomena occurs depends again on the position of the lines representing the internal equilibrium, especially in relation to the unmixing curves.

The foregoing brief account of the theory of allotropy proposed by Smits has been given mainly for the purpose of bringing one point to the attention of geologists and mineralogists: namely, that it aids in familiarizing us with the idea that pure phases (even crystalline) are not necessarily made up of a single molecular species, an idea which is supported by a considerable array of facts and is in conflict with no direct experimental evidence. In addition, it indicates that even metastable states, the existence of which has often been looked upon as a proof of lack of complete validity of physico-chemical principles, may also be treated theoretically.

Monotropic transformations.—Monotropic changes are irreversible; they occur when a form which is metastable under the particular conditions passes over into a form which is essentially stable under those conditions of temperature and pressure. Monotropic changes therefore occur whenever the rate of transformation becomes appreciable; moreover, since this rate is different under different conditions, the transition temperature is not a definite point but may lie within a very wide range. As an illustration consider the two principal forms assumed by calcium carbonate. All the evidence indicates that aragonite is metastable at temperatures above the ordinary; yet in the dry state it does not go over into calcite until about 400°. Yet the transition to calcite—which, being more stable, has at any definite temperature a lower vapor pressure and (in any single solvent) a smaller solubility than aragonite—takes place very slowly at 100° in presence of water, and more rapidly and at a lower temperature in presence of water containing

carbon dioxide; for carbon dioxide increases the solubility of both forms, and hence the rate of transformation.[1]

The occurrence of a real monotropic change implies that one modification of the substance involved is altogether metastable throughout its range of existence.[2] But we may have inversions which appear to be monotropic, but are in reality delayed enantiotropic changes; in such cases both forms of the substance have stable fields of existence, the apparent monotropy being due entirely to the sluggishness of transformation. A good example of this is shown in the silica diagram, as determined by Fenner.[3] Quartz, when heated in presence of a suitable flux, goes over slowly into tridymite at about 870°,[4] and the change is reversible; but when the quartz is heated without a flux, it goes over into β-cristobalite, the temperature at which this transformation occurs (about 1,400° or higher) varying with the rate of heating. β-cristobalite on cooling, in absence of a flux, does not return to quartz (or go over into tridymite), but at a temperature around 200° is transformed into α-cristobalite, which therefore at ordinary pressure must be altogether metastable. Thus transformations which are sluggish may appear to be monotropic until by the choice of an appropriate solvent medium their rate is so increased that their true character can be ascertained.

The temperature at which a monotropic change takes place can be influenced only by those factors which affect the rate of transformation; it will therefore be affected by the presence of impurities when the latter can act as fluxes and in this way increase the rate, but it will be unaffected by uniform pressure, because uniform pressure apparently has little or no influence on the rate of reaction, even where the reaction is attended by a large volume change. In

[1] It is to be observed that this argument of an increased solubility being attended by an increased rate of reaction must be used with caution; it will in general hold only when the original solubility was comparatively small.

[2] At least, at ordinary pressure. At higher pressures such a modification may have a stable field of existence; though up to the present there is no direct experimental evidence bearing on this point.

[3] *Jour. Wash. Acad. Sci.*, II (1912), 471. The system silica has also been investigated by Endell and Rieke, *Z. anorg. chem.*, LXXIX (1912), 239, and by Endell and Smits, *ibid.*, LXXX (1913), 176.

[4] This is the lowest temperature at which this transformation will take place. It occurs at all temperatures up to 1470°, at which point tridymite ceases to be the stable phase and is replaced by β-cristobalite.

accordance with this we have observed that a pressure even of 15,000 atmospheres (equivalent to a depth of perhaps 30 miles) is incompetent at room temperature to convert marcasite (sp. gr. 4.9) into pyrite (sp. gr. 5.0) nor did this change take place to an appreciable extent at 425° under 2,000 atmospheres pressure, although under ordinary pressure it does take place about 450°.[1]

Geologic thermometer.—The use of transformation and other points has been suggested as fixed points on a geologic temperature scale,[2] that is, as points of reference by means of which we may be enabled to fix the range of temperature within which certain processes have occurred or certain rocks or minerals have been formed. Such points should be chosen and used with caution. The only points free from objection are those transformations solid-solid which take place at a definite point with appreciable velocity and are not much influenced by pressure; in other words, we must choose rapid transitions which are accompanied by a small change of volume (or in the rarer case, by a large heat effect; or by both together). This is a serious limitation upon the number of satisfactory points, a limitation which must, however, be retained so long as our ignorance of the magnitude and character of the compressive stresses to which rocks have been subject remains complete, as in effect it now is. Melting-points could be used as points on the geologic thermometer only by postulating the purity of the substance and on the further improbable assumption that the compression has always been uniform; for, as we hope to show in a later paragraph, the effect of unequal pressure (shearing stress) upon the melting-point is so great that no conclusion of any value can be drawn except from such transition points solid-solid as remain unaffected by compression of any kind.

The use of transitions involving a gas or vapor phase is altogether indefensible. Take for instance the dissociation of calcium carbonate, according to the equation $CaCO_3 = CaO + CO_2$; to each temperature there corresponds a definite pressure of CO_2, a pres-

[1] G. Spezia (*Atti. Accad. Sci. Torino*, XLVI [1911], 1) has made a number of similar observations all of which are in complete harmony with the above statements.

[2] See Wright and Larsen, *Am. Jour. Sci.*, XXVII (1909), 421; *Z. anorg. Chem.*, LXVIII (1910), 338; J. Koenigsberger, *Neues Jahrbuch Min.*, Beilage Band XXXII (1911), 101, in which he makes a number of statements which require some reservation, as will be evident from what follows in the text.

sure which varies enormously with the temperature. Unequal pressure moreover affects such dissociations to a still greater extent than it influences melting-points. Transitions involving a vapor phase therefore can be employed as reference points when, and only when, we can accurately define the character and magnitude of the compression—a condition unlikely to be fulfilled in any instance of geologic importance at any time in the immediate future.

Occurrence of reactions in systems solid-solid.—This subject has been treated at some length in a recent communication from this laboratory;[1] so only the general conclusions will be presented here. Reaction may proceed at the surfaces of contact of adjacent grains of the constituents; but it by no means follows that reaction occurs in all systems where we might on other grounds judge that the stable state of the system would be that which obtains after reaction has taken place. The extent of the reaction will be increased by renewal of the surfaces of contact, and this may be effected by any agency which produces a kneading or grinding of the mass. Hence the reaction will be furthered by application of non-uniform (unequal) pressure (or in other terms, shearing stress), which moreover may also act in another way, the net result of which, however, is again to bring together new surfaces of contact. This will happen, namely, if the unequal pressure is of such character as to cause any of the original constituents or of the products of reaction to melt at the temperature of experiment; for then it will obviously further the reaction. Furthermore, non-uniform pressure can promote reaction by bringing adjacent grains into good contact; the reaction can then progress by diffusion across the area of contact. The effect of uniform pressure on reaction between solids is limited to this rôle, and therefore its effect is in general slight.

Interdiffusion of solids is appreciable in some systems: for instance, gold traveled into lead some 7 mm. in four years at room temperature, and about as far in as many weeks at 160°.[2] All the evidence indicates, however, that interdiffusion goes on only in

[1] J. Johnston and L. H. Adams, *Am. Jour. Sci.* (4), XXXV (1913), 205; *Z. anorg. Chem.*, LXXX (1913), 281.

[2] Roberts-Austen, *Phil. Trans. Roy. Soc. London*, A., CLXXXVII (1896), 383. For full information on this subject see "Report on Diffusion in Solids" by C. H. Desch, *British Assoc. Report* (Dundee, 1912); see also the recently published *Geologische Diffusionen* by R. E. Liesegang (Dresden: Steinkopf, 1913).

those systems in which solid solutions can form, as indeed one might expect a priori. The diffusion is enormously accelerated by rise of temperature, and may be influenced by pressure, though it would be premature to regard this as established yet, far less to generalize from it. In any case the rate of diffusion under geologic conditions, wherever diffusion is possible at all, is probably sufficient to reduce in the course of geologic time the degree of heterogeneity of systems which originally were not too coarse grained. Nevertheless old rocks frequently show well-defined layers of isomorphous crystals which, so far as we know, can form homogeneous mix-crystals; this is true especially for plagioclases, hornblendes, augites, and garnets, and indicates that in these cases the rate of diffusion is vanishingly small.

EFFECTS OF TEMPERATURE AND PRESSURE ON SYSTEMS SOLID-FLUID

General considerations.—In discussions of the change of volume (to take a specific instance) which accompanies the process of melting, one often encounters the argument that this change is given by the difference between the densities of the crystals and of the glass, as measured at ordinary temperature. This argument may be altogether misleading, because it involves the tacit assumption that the expansion coefficients of both crystals and glass are identical—an assumption which certainly can fit the facts only in a few exceptional cases.[1] Of course until the necessary quantities have been actually determined, one can only use the densities observed under ordinary conditions; but if one does so, the limitations of any results calculated in this way must be recognized, and the conclu-

[1] The truth of this statement is perhaps more obvious from the following mathematical formulation. If V_l and V_s are the specific volumes of glass and crystals, respectively, at ordinary temperature, the change of volume

$$\Delta V = V_l - V_s \, .$$

The change of volume at the temperature t is

$$\begin{aligned}\Delta V_t &= (V_l + \Delta V_l) - (V_s + \Delta V_s) \\ &= \Delta V + (\Delta V_l - \Delta V_s)\end{aligned}$$

where ΔV_l and ΔV_s are the expansion produced by the increased temperature in glass and crystals, respectively. The term $(\Delta V_l - \Delta V_s)$ may be positive or negative, and might even be of such magnitude as to cause the sign of ΔV_t to be opposite from that of ΔV, if the latter were itself small.

sions regarded as tentative and preliminary only. Precisely similar remarks apply to the effect on this volume change of pressure alone or of pressure and temperature combined.

The computation of heats of reaction for conditions differing from those under which the experimental values were determined is subject to altogether analogous limitations, the specific heat, or change of heat capacity, being the exact analogue of expansion coefficient. In this case indeed we may have—although to be sure the experimental data are not very concordant—an instance of reversal of the heat effect of a reaction with rise of temperature. The heat of transformation aragonite → calcite at 20° is small, probably positive and less than 1 cal. Now according to the most thorough series of measurements for aragonite and calcite,[1] their mean specific heats within the range 0°–300° (the limit of the measurements) are respectively 0.2246 and 0.2204; hence the difference is 0.004 per degree or about 1.8 cal. for 450°. Therefore the heat of transformation at 470° will be 1.8 cal. *less* than it is at 20°, and thus a minus quantity; this is in agreement with the observations of Lashchenko,[2] who concluded that this transformation at 470° is accompanied by the absorption of considerable heat.

Variation of effects of compression with its character.—There is a marked difference in the effect of compression according as it is uniform or otherwise. Changes in the physical properties of substances are induced by uniform pressure, but disappear when the pressure is removed. Non-uniform compression produces permanent deformation of bodies exposed to it, and therefore causes permanent alterations in many of the physical properties of the substance. The effects of the latter differ so much from, and so far outweigh those of uniform pressure, both in character and in magnitude, that it is advisable to treat them separately.

Uniform pressure is, by definition, the same in all directions; in practice, however, this is not altogether easy of attainment at really high pressures, because then the liquids generally used to

[1] Lindner, *Sitzber. physik. medizin. Ges. Erlangen*, XXXIV (1902), 217.

[2] Lashchenko, *Jour. Russ. Phys. Chem. Soc.*, *XLIII* (1911), 793. It may be noted, however, that Boeke, who used a differential method, concluded that the heat change at 470° is less than 0.5 cal. (*Z. anorg. Chem.*, *L* [1906], 246).

transmit pressure become exceedingly viscous.[1] A non-uniform compression may always be resolved into a shearing stress and a (smaller) uniform pressure, the former being the preponderating factor in producing the results observed. Now a consistent account of all the experimental work can be given if we make the plausible assumption that the shearing stress acts on the solid phase, but not on the liquid phase; in accord with this, in non-uniform compression the liquid (fluid) phase would be subject to less pressure than the solid phase, whence the name "unequal pressure" chosen to designate this type of compression.[2]

EFFECT OF UNIFORM PRESSURE ON MELTING-POINTS

Thermodynamical considerations lead directly to the differential equation

$$\frac{dT}{dp}=\frac{TdV}{\Delta H} \tag{I}$$

which expresses the change of melting-point (dT) with change of pressure (dp) in terms of T, the absolute temperature of melting, dV, the volume change and ΔH, the heat change which accompanies melting of the substance at T. Before this equation can be applied it must be integrated, since we are dealing with finite changes.

In order to integrate this equation rigorously it is necessary to know how dV and ΔH vary with pressure and temperature. The exact magnitude of these variations is not known in general; but, fortunately, their effect is slight and may for most practical purposes be neglected. We may consequently use the following form of the equation to calculate the change of melting-point (ΔT_2) produced by a change of pressure (ΔP_2, expressed in atmospheres[3]):

$$\frac{\Delta T_2}{\Delta P_2}=\frac{T(V_l-V_s)}{41\cdot 30\ Q} \tag{II}$$

[1] For instance, at 20,000 atm. and ordinary temperatures, even gasoline becomes quite viscous (approximately, perhaps, of the consistency of vaseline).

[2] A fuller discussion of this topic, together with many references to previous work, will be found in a paper by Johnston and Adams, *Am. Jour. Sci.* (4), XXXV (1913), 205; *Z. anorg. Chem.*, LXXX (1913), 281; cf. also *postea*.

[3] That is, true atmospheres (1,033 g. per sq. cm.).

wherein Q is the heat (absorbed) of melting in calories per gram, and V_l and V_s the respective volumes of 1 gram of substance at the melting-point in the liquid and the solid state. An example of the agreement between calculation from this formula and actual observation of the effect of pressure on the melting-points of tin, bismuth, cadmium, and lead is afforded by the following table, taken from a former paper from this laboratory;[1] the divergences are such as are to be expected in view of the present uncertainty in the values of Q, the latent heat of melting:

TABLE I

EFFECT OF UNIFORM PRESSURE ON THE MELTING-POINTS OF CERTAIN METALS

Metal	Latent Heat cal. per gram Q	Vol. Change on Melting $V_l - V_s$	ΔT per 1,000 atm. calc. from Equation II	ΔT per 1,000 atm. observed
Sn.........	14.25	0.003894	+3.45	+3.28
Cd........	13.7	0.00564	+6.10	+6.29
Pb........	5.37	0.003076	+8.59	+8.03
Bi.........	12.6	−0.00342	−3.67	−3.55

Equation II enables us therefore to calculate the effect of uniform pressure on melting-point if certain physical constants of the material are known; unfortunately, however, these constants are known for very few substances, among which are practically none of direct geologic interest.

Direct determinations of the effect of pressure on melting-point have been made only as follows: potassium,[2] sodium,[3] mercury,[4] water,[5] and a large number of organic substances[6] (e.g., benzol, phenol, naphthalene, etc.) including several substances capable of existence as a liquid-crystalline phase.[7] All of these

[1] Johnston and Adams, *Am. Jour. Sci.*, XXXI (1911), 516; *Z. anorg. Chem.*, LXXII (1911), 29.

[2] Tammann, *Krystallisieren und Schmelzen*. [3] *Ibid.*

[4] P. W. Bridgman, *Proc. Am. Acad.*, XLVII (1912), 349; *Z. anorg. Chem.*, LXXVII (1912), 377.

[5] *Proc. Am. Acad.*, XLVII (1912), 441.

[6] Tammann, *loc. cit.;* Hulett, *Z. physik. Chem.*, XXVIII (1899), 629 (pressures only up to 300 atm.).

[7] Hulett, *loc. cit.;* Körber, *Z. physik. Chem.*, LXXXII (1913), 45.

investigations show that the change of melting-point for the first 1,000 atm. is less than 40°;[1] further, that for each succeeding 1,000 atm. the effect is progressively less, a fact which indicates that no maximum melting-point is realizable (if indeed it is possible).

There are only two substances for which a lowering of melting-point by uniform pressure is established, namely, water and bismuth; and with water only at pressures up to about 2,100 atm. (where the m.p. is −22°), above which the melting-point rises steadily with pressure, reaching +76° at 20,000 atmospheres. There may be a few other substances belonging to this category but their number is certainly small. In general, therefore, uniform pressure raises the melting-point; so that we may say that uniform pressure increases the rigidity of material—an increase which becomes very noticeable with substances (e.g., the oils commonly used to transmit pressure) whose freezing-point is not far removed from the ordinary temperature.

EFFECT OF UNIFORM PRESSURE ON SOLUBILITY

The influence of temperature upon the solubility of solids varies greatly from one substance to another; the more common effect is an increase of solubility with temperature, but there is a large number of substances (e.g., $Ca(OH)_2$, $CaSO_4 2H_2O$, to name two common ones) whose solubility decreases with rise of temperature. The direction and magnitude of this change of solubility is determined by the sign and magnitude of the heat of solution; an absorption of heat corresponds to an increase of solubility with temperature, an evolution of heat to a decrease. In applying this criterion, one must take care to choose the heat effect[2] appropriate to the dissolution of the particular solid phase which is in equilibrium with the solution under the particular conditions; for instance, to use the heat of solution of $Ca(OH)_2$, not of CaO, and at temperatures

[1] With one exception, camphor, where 300 atm. pressure raised the melting-point by 38.7° (Hulett, *loc. cit.*).

[2] The heat effect to be used is always that observed when 1 mol. of the solid is dissolved in a large volume of a solution nearly saturated with respect to the solid in question.

above 32.4° to use the (positive) heat of solution of Na_2SO_4 (anhydrous), at lower temperatures the (negative) heat of solution of $Na_2SO_4 10H_2O$ which is then the stable solid phase in solution.

The effect of uniform pressure on the solubility of solids can be calculated from an equation analogous to equation I whenever the heat effect and volume change appropriate to the particular conditions are known. Hitherto trustworthy direct determinations have been made for only four substances,[1] of which but one is even of indirect geological significance; the mean values obtained are given in the subjoined table.

TABLE II

CHANGE OF SOLUBILITY PRODUCED BY UNIFORM PRESSURE (COHEN AND COLLABORATORS)

Pressure in Atmospheres	$CdSO_4 8/3H_2O$ at 25°		$ZnSO_4 \cdot 7H_2O$ at 25°		Mannite at 24.05°		NaCl at 24.05°	
	Conc. of Satd. Solu. g. $CdSO_4$ per 100 g. H_2O	Percentage Change	Conc. of Satd. Solu. g. $ZnSO_4$ per 100 g. H_2O	Percentage Change	Conc. of Satd. Solu. g. Mannite per 100 g. H_2O	Percentage Change	Conc. of Satd. Solu. g. NaCl per 100 g. H_2O	Percentage Change
1....	76.80	.....	57.95	.....	20.66	.....	35.90	.....
500....	78.01	+1.57	57.87	−0.14	21.14	+2.32	36.55	+1.81
1,000....	78.84	+2.68	57.65	−0.52	21.40	+3.57	37.02	+3.12
1,500....	.....	.....	.....	.....	21.64	+4.72	37.36	+4.07

From this we see that it would be likely to require a very considerable change of (uniform) pressure to change the solubility by 50 per cent, a change which may easily be produced by a comparatively small change of temperature. Hence the influence of pressure on the solubility of solids is altogether negligible in comparison with the influence of temperatures.

Uniform pressure may cause marked increase in the apparent solubility in certain cases; namely, wherever we are really dealing with an equilibrium, the state of which is displaced by pressure. An example of this is afforded by calcium carbonate in presence of water and carbon dioxide; increased pressure increases the concentration of CO_2 in the water (and hence really changes the character

[1] E. Cohen and L. R. Sinnige, *Z. physik. Chem.*, LXVII (1909), 432; LXIX (1909), 102; E. Cohen, K. Inouye, and C. Euwen, *ibid.*, LXXV (1911), 257. These authors give a critical résumé of earlier work along this line.

of the solvent) and thus produces a greater apparent solubility of the $CaCO_3$. Moreover, the solubility of solids in fluids at temperatures above the critical point of the solution will be dependent on the pressure, since the effect of the latter is then to change the concentration of the solvent, just as pressure affects the solubility of gases, by changing the concentration of the solute itself, and hence the concentration of the solute in the solution.[1]

One point remains to be noticed, namely, that in making use of solubility data we must remember that solubility, and the heat effect and volume change accompanying dissolution of a substance, are affected by the presence of other substances[2] in the solvent. Now from a complex solution from which any one of a number of substances can conceivably separate out first, the product which actually separates out is that which under the particular actual conditions is least soluble, or has reached its limit of saturation.[3]

Solubility relations are therefore of the highest importance; but they must always be determined under the proper conditions, and cannot be inferred from the relative solubilities of the various substances in pure water.

Importance of solubility relations in determining the course of a reaction in solution.—The importance of this fact—that solubility (or perhaps we should rather say, lack of solubility) is the predominating factor in determining the order of separation of the products of reaction of any system—is not so universally appreciated as it ought to be. The appearance of any one product is very often ascribed to the existence of a greater affinity between its component parts than exists between the components of the other compounds which might conceivably be formed by the reaction. In a certain sense this is true, but in the sense in which the term

[1] This question is discussed later.

[2] The following are two extreme examples, which illustrate the two main modes of action of added substances. $Ag(CN)_2$ is very sparingly soluble in water, but quite soluble in water containing KCN, owing to the formation in this case of the complex $KAg(CN)_2$. The solubility of AgCl, on the other hand, is much smaller in water containing KCl (or $AgNO_3$), owing to the effect of the common ion Cl' (or Ag^+).

[3] This is the basic principle underlying van't Hoff's great series of investigations of the oceanic salt deposits.

affinity is ordinarily employed it is fallacious and misleading. For example, consider the following reactions:

$$AgNO_3+BaCl_2 = 2\mathit{AgCl}+Ba(NO_3)_2$$
$$Ba(NO_3)_2+Ag_2SO_4=\mathit{BaSO_4}+2AgNO_3$$

From the first of these, we should, according to the above reasoning, conclude that silver was a stronger base than barium; while from the second, we reach the directly opposite conclusion.

As another example, take the statement (which appears in the majority of textbooks on organic chemistry) that tetramethylammonium hydroxide ($N(CH_3)_4OH$) cannot be displaced from aqueous solutions of its salts (e.g., the chloride) by potassium hydroxide because the former is the stronger base. But it has been shown that if we choose a medium (methyl alcohol) in which one of the products (potassium chloride) of the reaction is insoluble, the reaction

$$N(CH_3)_4Cl+KOH=N(CH_3)_4OH+\mathit{KCl}$$

takes place and yields practically the theoretical amount of the tetramethylammonium hydroxide.[1] These two examples, which are typical of a very large number of similar cases, demonstrate that the relative strength of the competing acids and bases is a negligible factor in determining the product which separates out following a reaction in aqueous (or other) solution; the important factor is the relative solubility limits of the original substances and of the possible products of reaction.[2] This behavior is in thorough accordance with the law of mass action and with the currently accepted theory of solution; so that if we knew the solubility relations of all possible products (including complex salts, e.g., the double cyanides and oxalates, if such are possible) we could predict quantitatively the course of the reaction.

Another good example, which at the same time illustrates another point, is this. If we add hydrochloric acid to a solution of sodium silicate, sodium chloride will be formed and silicic acid (in

[1] Walker and Johnston, *Jour. Chem. Soc.*, LXXXVII (1905), 955.

[2] This statement is subject to slight limitations, which, however, are of minor importance, and hence need not be discussed here. Their effect is such that a lack of concordance of 1 or 2 per cent may be found between theory and practice.

the form of gelatinous silica) liberated; but yet at a very high temperature, as in the process of glazing earthenware, silicic anhydride in presence of water vapor is capable of decomposing sodium chloride with expulsion of hydrochloric acid. This behavior is not at first sight dependent on solubility relations; but it is perfectly analogous if we consider that volatility may be looked upon as solubility in a vacuum as solvent. We can therefore extend the statement of the preceding paragraph and say that the factor which determines the result of heating together a number of substances at high temperatures is lack of solubility or of volatility, the substance which tends to appear being that which under the particular equilibrium conditions is least soluble or least volatile.

THE LAW OF MASS ACTION AND THE REACTION CONSTANT K

Consider the reversible chemical action

$$A+B \leftrightarrows C+D$$

where the letters represent single molecules of the substances as in ordinary chemical formulae. Then according to the law of mass action the state of equilibrium of the above system is determined by the equation[1]

$$\frac{[A]\,[B]}{[C]\,[D]}=K$$

where the symbols [A], [B], etc., represent the "active masses" *at equilibrium* of the respective substances; K is a constant, the value of which depends solely on the external conditions (e.g., temperature) but is independent of the total amount of material present. When the reaction takes place in a wholly gaseous system, the active mass of each substance is proportional to its molecular concentration or partial pressure. When the system is an aqueous

[1] When the reaction is $nA+mB \leftrightarrows pC+qD$ (that is, where more than one molecule of any (or all) of the substances enters into the reaction) the expression for the reaction constant is

$$\frac{[A]^n[B]^m}{[C]^p[D]^q}=K$$

In this case attention must be paid to the unit of concentration employed except when $m+n=p+q$, as the numerical value is then dependent on the unit of concentration employed.

solution, the active mass of each reacting molecular species (which are, according to the current views, ions and undissociated molecules) is given by the concentration of that particular species in the unit of volume (expressed always in molecular, or equivalent, concentrations). It should be observed that K is found to be constant only in dilute solutions (and correspondingly, in gaseous systems only at low pressures); but there is no doubt that its lack of constancy at greater concentrations (or pressures) is due altogether to our lack of accurate knowledge of the real concentrations (partial pressures) of the reacting molecular species. The reaction constant K is independent of the amounts of the various substances originally present, so long as the temperature and pressure remain constant; its dependence on temperature (at constant pressure) is given by the equation[1]

$$\frac{d\ln K}{dT} = \frac{Q}{RT^2} \qquad \text{(III)}$$

Hence if we know K at any one temperature, and the heat change Q accompanying the reaction,[2] we can calculate K at any temperature; conversely from the values of K at various temperatures, we can compute mean values of Q.

Similarly, the variation of K with (uniform) pressure, at constant temperature, is given by the equation

$$\frac{d\ln K}{dp} = -\frac{\Delta V}{RT} \qquad \text{(IV)}$$

where ΔV is the increase of volume accompanying the reaction when 1 mol. is transformed. This equation holds strictly in homogeneous systems; where solid substances are present, it is essential that they be subject to the same uniform pressure as the rest of the system. The equation is the quantitative formulation of the statement that increase of pressure tends to displace the equilibrium in the direction in which the reaction is accompanied by decrease of volume.

[1] $\ln K$ is $\log_e K = 2.303 \log_{10} K$.

[2] For exact work we must know further how Q varies with temperature; the assumption of a constant value of Q, however, leads to results sufficiently exact for most purposes. Further, our knowledge of Q at any one temperature usually leaves much to be desired, not to speak of its variation with temperature.

In a completely fluid system the influence of pressure on the position of equilibrium will not in general be large, because the volume change ΔV is usually small. In gaseous systems the direction of the effect can readily be predicted, since the volume of a gas (at constant temperature and pressure) is a direct measure of the number of molecules of it present. Therefore pressure is without effect if the total number of molecules remains unchanged by the reaction; otherwise, it displaces the position of equilibrium toward the side with the smaller total number of molecules.

In heterogeneous systems liquid-gas and solid-gas the pressure changes the concentration in the gas phase, and in this way may have very considerable effect on the position of equilibrium.

The action of *unequal* pressure, however, on a heterogeneous equilibrium is of an entirely different order of magnitude. If a system solid-liquid or solid-gas is compressed in such a way that the fluid phase can escape continuously, the reaction will be driven in one definite direction. For example, if the system

$$RCO_3 + SiO_2 \rightarrow RSiO_3 + CO_2$$

is compressed in such a way that the CO_2 escapes, $RSiO_3$ will always be formed. Then, too, unequal pressure influences greatly the solubilities of solids, and thus may entirely change the relative concentrations of the solid substances in the fluid phase.

The foregoing paragraphs provide a basis for the observation that metamorphosed rock is usually denser than that from which it was formed, for the so-called *Volumgesetz* of the Germans. To this rule there are many exceptions; the extent to which it holds is about what we might expect; for while pressure tends to produce denser material, it may not actually do so if the rate of reaction is very small under the particular conditions. Moreover, we cannot safely conclude from measurements of specific volume made at ordinary temperature (as all of them hitherto have been) that the change of volume under the actual conditions of transformation was the same in magnitude or even in sign; for, as we have already pointed out, a difference (such as may easily occur) between the coefficients of expansion of the substances concerned may cause a reversal of sign of the volume change, especially when the latter is small.

As an application of the law of mass action to a very simple case, consider the dissociation of calcium carbonate according to the equation

$$CaCO_3 \leftrightarrows CaO + CO_2 .$$

We will presume that the reaction takes place in the gaseous phase: the equilibrium constant is then given by the equation

$$\frac{(CaO)\,(CO_2)}{(CaCO_3)} = C ,$$

the quantities in parentheses denoting the partial pressure at equilibrium of the substance written within the parentheses.[1] Now CaO and $CaCO_3$ are always present in the solid phase, from which it follows that at any one temperature (CaO) and ($CaCO_3$) are constant; whence we have $(CO_2) = K$. In other words the pressure of CO_2 in equilibrium with a mixture of CaO and $CaCO_3$ is independent of the amounts of the solids present, and has a definite value for every temperature;[2] its variation with temperature being given by equation III.

E. Baur[3] has investigated a system of considerable geologic interest, namely, the reaction

$$SiO_2 + 4HF \leftrightarrows SiF_4 + 2H_2O$$

which takes place when aqueous hydrofluoric acid is distilled in presence of excess of silica. Under these conditions SiO_2 is solid, the other three substances gaseous; therefore at definite temperature and pressure we should find that the expression

$$\frac{(SiF_4)\,(H_2O)^2}{(HF)^4} = K .$$

[1] It may be objected that it is absurd to talk about the vapor pressure of a substance such as CaO; we have, however, every reason to believe that such pressures, though infinitesimal, are real and perfectly definite. Application of the mass law to the vaporization of CaO, that is, to the reaction CaO (solid) $\rightarrow$ CaO (vapor), gives the relation $\frac{(CaO)}{CaO\ (solid)} = K'$; but since excess of solid is present, CaO (solid) is constant and therefore at constant temperature $(CaO) = K''$.

[2] These values may be found in Johnston, *Jour. Am. Chem. Soc.*, XXXII (1910), 938.

[3] *Z. physik. Chem.*, XLVIII (1904), 483.

The actual determination of the various concentrations is very difficult, so that moderate concordance between the values of K is all that can be expected. At 104°, K is of the order of 2×10^9, at 270° it is about 5×10^7. This decrease of K with rise of temperature shows that the equilibrium is displaced toward the left by rise of temperature, so that the reaction, as written above, is at these temperatures slightly exothermic. The influence of pressure is easily predicted; for, since we have 3 volumes on the right side, as compared with 4 volumes on the left (the volume of the solid silica is, in comparison, negligible), pressure will displace the equilibrium toward the right-hand side of the equation above. From the above it follows that, when such vapors escape from the magma, lowering of their temperature alone will result in a dissolution, instead of a precipitation, of SiO_2; decrease of pressure, on the other hand, results in the production of quartz—an effect which will presumably predominate over that produced by decrease of temperature, since the volume change is large but the heat change accompanying the reaction comparatively small.

Constant solubility product.—Again we can readily deduce from the mass-action law the experimental fact of the constancy of the so-called solubility product. Thus for the substance AgCl we find that

$$(Ag^+)\,(Cl^-)=K$$

where (Ag^+) and (Cl^-) represent the real concentrations of silver ions and chlorine ions in the solution; K is a constant, depending only upon the temperature. This relation holds true for any solution in which silver ions and chlorine ions may be present together in contact with solid AgCl—no matter what other ions may also be present—provided always that (Ag^+) and (Cl^-) are understood to be the *real* concentrations of the respective ions, when equilibrium has been attained.

As a specific example of the application of this principle to the determination of equilibrium conditions, we shall consider the reversible reaction

$$BaSO_4+Na_2CO_3\leftrightarrows BaCO_3+Na_2SO_4\ .$$

There are present in the system the following molecular species: un-ionized $BaSO_4$ and $BaCO_3$, Ba^{++}, SO_4'', CO_3'' (and Na^+, which,

however, may be left out of account, since it plays no direct part in the reaction).

We have then the equilibrium equations between these quantities

$$[Ba^{++}][SO_4''] = K_1 \text{ and } [Ba^{++}][CO_3''] = K_2$$

where K_1 and K_2 are the solubility products of $BaSO_4$ and $BaCO_3$, respectively; and therefore, since $[Ba^{++}]$ is common to both,

$$[SO_4'']/[CO_3''] = K_1/K_2 = K .$$

In words, the ratio of the concentrations of sulphate ion and carbonate ion is constant. Therefore, if, after equilibrium has been attained, we add SO_4'' (as Na_2SO_4), $BaCO_3$ is transformed into $BaSO_4$, until this ratio reattains its constant value; conversely the addition of CO_3'' causes the formation of $BaCO_3$ at the expense of the $BaSO_4$. In each case the amount transformed is perfectly definite; and the state of equilibrium can always be calculated if K_1, K_2, and the concentration of either SO_4'' or CO_3'' are known. If the conditions were such that the system should become saturated with respect to sodium sulphate or carbonate (or both), the equation determining the equilibrium would be somewhat more complicated; but the general result would be the same, namely, that the position of equilibrium is determined by the relative solubilities (in the particular medium) of such of the possible products of reaction (which include the original substances) as separate out as solid phases.

On this basis we can readily see why it may be that carbonic acid may displace silicic acid from a solution of a silicate at low temperatures, while at high temperatures the silicic acid may displace the carbonic acid and regenerate the silicate; and that it is unnecessary to bring in the conception of affinity or strength of acids to account for the phenomena observed. Nor is it necessary to attribute the reversal in aqueous solution of reactions such as the above to the influence of pressure, as is frequently done. It is true that pressure is required in order to retain the volatile components, the concentration of which in the vapor phase is thus determined by the pressure; but it is limited to this more or less subsidiary rôle. The predominating factor in determining the state of equilibrium in solution is temperature, which acts primarily

through its effect on the solubility relations of the substances involved in the reaction; secondarily and much less generally, through its effect on the hydrolytic dissociation of salts.

Salt hydrolysis.—It is a matter of common knowledge that the aqueous solutions of many salts are not neutral; thus for instance sodium carbonate, sulphide, and silicate are alkaline; the chlorides, nitrates, and sulphates of most polyvalent bases are acid. This behavior is attributed to a process termed salt hydrolysis, which may be represented by the reaction

$$BA + H_2O \leftrightarrows BOH + HA$$

and occurs (to an appreciable extent) only when the acid, or the base (or both),[1] is weak.[2]

It is impossible to enter here into the theory of hydrolysis, or to derive from the law of mass action the relations which determine its extent. Suffice it to say that under constant external conditions the extent of hydrolysis is perfectly definite, and depends upon the magnitude of the dissociation constant of the weak acid[3] or the weak base;[4] or rather on the relation between this dissociation constant and that of water; so that the process of hydrolysis may be regarded as a competition for the strong base (or acid) between the weak acid (or base) and water (which may exercise either basic or acidic functions). Thus in decinormal solution at ordinary temperatures: sodium chloride is practically not hydrolyzed, sodium acetate is hydrolyzed to an extent which is just appreciable (0.01 per cent), while sodium sulphide or silicate is hydrolyzed to somewhere about 90 per cent. With rise of temperature the dissociation constant of water increases faster than that of the acids and bases; consequently the extent of hydrolysis increases markedly with rise in temperature.

[1] This case is of less practical importance, hence its consideration is omitted here.

[2] The strength of an acid (or base), in the sense in which it is used here, is measured by its extent of ionization. Thus, in decinormal solution at 25°, hydrochloric acid is ionized to about 85 per cent; acetic acid to about 1 per cent; hydrogen sulphide to about 0.1 per cent; corresponding to this the respective dissociation constants of these acids are 1 (approximately), 1.8×10^{-5} and 9×10^{-8}. The dissociation constant of water at 25° is 1.2×10^{-14}.

[3] In salts which yield an alkaline solution.

[4] In salts which yield an acid solution.

Of the hydrolysis of the silicates little is definitely known, except that the ordinary solutions of alkali silicates (water glass) are nearly completely hydrolyzed into free alkali and colloidal silica. But from this it is not quite safe to conclude that the salts corresponding to all of the silicic acids (or aluminosilicic acids,[1] if such salts exist) are also completely hydrolyzed under all conditions. For it is quite conceivable that hydrolysis of a silicate may take place without producing colloidal silica; this might occur either because the silicic acid resulting from hydrolysis of the particular silicate is not colloidal or because of the intervention of factors—temperature, or the presence of other substances in the solution—which enhance the *real* solubility of silica and thus decrease its tendency to appear in colloidal form. The extent of hydrolysis under such conditions would be that corresponding to the dissociation constant of the silicic acid, which may not be so small as is commonly supposed. For in the hydrolysis of silicates, as it has been observed, the silica becomes colloidal and is removed from true solution as fast as it forms, and hence its active mass in the solution remains exceedingly small; consequently the hydrolytic dissociation continues until practically all of the original silicate is decomposed. This therefore affords us no *certain* information as to the strength of the silicic acid, for the same phenomenon would be observed even if the silicic acid were of such strength (e.g., comparable to acetic acid) that the extent of hydrolysis is of the order of 0.1 per cent; furthermore, it is no absolute criterion of what would happen if no colloidal material were formed.

The rôle of hydrolysis is important in the kaolinization of the feldspars, and in many reactions occurring in solution in liquid water; but in all probability it is altogether subsidiary—if not entirely negligible—under magmatic conditions, in which case it is preferable to regard the silicate mixture as solvent and the water (or other gases) as solute.

Most silicates react alkaline in contact with water; but according to F. Cornu,[2] an acid reaction is given by a number of minerals,

[1] To illustrate by means of an analogous case: the salts of hydrocyanic acid (HCN) are largely hydrolyzed, whereas there is very little hydrolysis with salts of hydroferrocyanic acid ($H_4Fe(CN)_6 = 4HCN, Fe(CN)_2$).

[2] Tschermak's *Mitt.*, XXIV (1905), 417.

such as hibschite, kaolin, pyrophyllite, nontronite, all closely related to the kaolin formula $R_4Al_2Si_2O_9$. Now the reaction between complex silicates and water is not necessarily simple; for instance, the reaction may be due to hydrolysis of the first products of decomposition of the silicate. Moreover, atmospheric carbon dioxide might play a part in the reaction. In this connection it is well to observe that it is incorrect and useless to speak of the *solubility* of a mineral in water, unless the mineral dissolves as a whole; just as it is useless to speak of the solubility of a metal in an acid. We may speak of solubility only when the relations between the various components are the same in the solution as in the solid, or when it is possible to recrystallize the original silicate from the solution. Otherwise we are dealing, not with a process of solution, but with a decomposition.

DIASTROPHISM AND THE FORMATIVE PROCESSES. I[1]

INTRODUCTION

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During the century or more throughout which a gaseous origin and an early molten state of the earth were accepted tenets a full system of doctrines relative to the formative and deformative processes of the earth was elaborated. In the earlier portions of the period these were largely based on the hypothesis of a thin crust floating on a liquid substratum. Later in the period various views of partial solidity grew up and modified the older tenets or replaced them with others. In more recent times essentially complete solidity has come into wider favor and been made the basis of more radical modifications. But these views of solidity were in the main derivatives from the original postulates of a gaseous origin merging into a molten state and they retained the presumptions appropriate to such earlier history. There thus ran through the whole system of tenets a thread of philosophy that shaped it in harmony with the initial assumptions. It is true that particular tenets were not always consistent with the system into which they were introduced, but this is only an inevitable incident. The solid earth of this philosophic lineage was usually of the type that holds rigidity to be but a function of viscosity. The tenets of formation and deformation built upon it embraced a doctrine of flowage of a slow secular sort directed by the principles of liquid motion restrained by viscosity. The presumption that such slow motion would take place under any appreciable stress if given time enough was a common tenet held widely and firmly. Specific doctrines of deformation and of secular tidal effects were worked out with great labor and skill on the basis of a visco-solid and even a visco-rigid earth. The tenets thus based on a solid and even highly rigid earth rounded

[1] Largely the results of studies pursued under the joint auspices of the Carnegie Institution of Washington and the University of Chicago.

out the older systems of doctrine founded on a more mobile earth into a fairly complete working scheme of inquiry and elucidation.

There were indeed individual instances in which the view of an elastico-rigid earth was entertained and yet regarded as springing from an earlier gaseo-molten state. But while thus entertained, this conception of an elastico-rigid earth was not carried out into a working system of doctrines consistent throughout with itself. There never grew out of it a panoply of tenets on which the geologist could base working hypotheses suited to his special problems on clear lines free from confusion with the tenets that sprang from a visco-solid earth. The instructor in geologic philosophy was never able to point the embryo geologists under his training to a set of views built distinctly on the working hypothesis of an elastico-rigid earth.

But aside from this deficiency, as already remarked, a quite ample system of tenets, with alternatives and divergences, has been developed, covering the full range of conceptions from the picture of an earth with a thin shell and molten interior through various grades of partial solidity up to dominant visco-solidity of a high order of rigidity.

So familiar have most of these tenets become that they often seem to stand by themselves quite independent of the hypotheses on which they were founded. By long currency they seem to have lost much of the speculative elements that really enter into them. This is not only a source of danger in itself but is likely to stand in the way of an impartial adjudication of less familiar conceptions that are not more speculative but merely seem to be so, and which are perhaps guarded by a more frank recognition of the speculative elements.

The strong support which new evidences from cognate sciences lend to the doctrine of an elastico-rigid earth, in distinction from a visco-solid earth or any form of fluidal earth, adds emphasis to the need for a system of tenets that are strictly loyal to the elastic principle. While the principles are thus loyal, the working hypotheses must obviously recognize that, though the earth may be dominantly an elastico-rigid body, it is not exclusively so. The gaseous and liquid elements are factors of moment and co-operate in

the great processes that form the earth-habit, but in this set of views it is to be assumed that they serve as subordinate elements and merely condition the dominance of elastic solidity.

The development of a system of tenets on the elastico-rigid basis is also invited by the grave objections that have arisen from new phenomena against the gaseous cosmogony and its sequences which lie back of the older system of tenets. The planetesimal cosmogony offered to meet these difficulties is founded on orbital mechanics and parts company with gaseous mechanics at the outset. Being thus dynamically diverse from the start, it has occasion for its own set of tenets. These need elaboration to meet the whole range of phenomena involved in the major problems of geology. The task of working these out has been steadily pursued but the labor is great, and progress, if guided by prudence and circumspection, is necessarily slow.

While many of these tenets of course have no immediate concern with the physics of the body of the earth and are not necessarily of the elastico-rigid order when they do, yet the dominant tendency from the nature of the hypotheses is in that direction. The planetesimal cosmogony opens the way at least for the evolution of an elastico-solid earth in the very mode of growth it postulates, though it does not exclude the possibility of a molten earth or even the probability that molten and gaseous states may dominate planets much more massive than the earth. With a body of the mass of the earth limited in its power to control the lighter gases, the trend of probabilities favors an essentially solid earth from an early stage of growth if not from the very beginning. An orbital organization may have dominated even the earth-nucleus of the parent nebula. At any rate, the long slow growth of the main mass of the planet offers rather strong presumption of a relatively cool solid accretion attended by heterogeneities of composition and differentiations of accession and crystalline organization that were never smoothed out by liquefaction but have remained of the same type as those now presented by the earth. An elastico-solid state is thus rather a matter of direct genesis than of subsequent derivation as is the case in the alternative mode of origin.

Following this hypothesis, therefore, one comes to a mature

earth with internal qualities closely like those of the accessible parts of the present body, and the working tenets that spring from this hypothesis most naturally are those founded on crystalline structure dominated by elastico-rigid properties. The conception is free from the inheritances of a liquid state with its inevitable assortments and systematic arrangements of material on the basis of specific gravity.

The conceptions of internal temperature and of vulcanism associated with this hypothesis by its author[1] are peculiarly hospitable to the development and maintenance of a solid crystalline state of the interior. They are relatively free from the postulate of very high temperatures. No occasion for a rise to the critical temperatures of rock-substance is offered and the dilemmas these bring do not trammel the problems of the planetesimal earth of the author. It is immune against the gaseous heart. The very mechanism of its vulcanism automatically forces to the surface the expansional factors that contribute to liquefaction and the gaseous state. The elements that, if retained, would lend mobility to its mass continually seek the surface, while those that contribute to stability and solidity remain within. The normal earth-habit under this hypothesis is conducive to a stable crystalline organization. This holds to as great depths as known methods of action may be safely projected. As balanced pressure contributes to solidity, it is a hazardous assumption that places narrow limits to the downward extent of solidity and the crystalline state.

Deep differentiations of specific gravity of moderate degree are natural results of a slow planetesimal growth under the conditions imposed by the early atmosphere and hydrosphere, in addition to the inequalities of infall. The inevitable deformations and gradational processes of the growing stages are presumed to have emphasized these inequalities, in certain respects, in modes of the same sort as those that affected all later history. These inherited inequalities of specific gravity are, perhaps more than any other agency, the governing power in shaping if not actuating diastrophic movements. This is the basis on which isostasy today does whatever it is competent to do toward a final equilibrium. How such a basis for

[1] "The Bearings of Radioactivity on Geology," *Jour. Geol.*, XIX, No. 8 (1911).

action could have arisen from a primitive fluidal condition is the task of those who postulate that state.

Under the planetesimal hypothesis, the earth grew slowly into the state which it still in the main retains, dominated by working methods of the same order as those that now prevail. No radical change of working tenets between the formative and the subsequent stages is required.

As already stated, the formative stages of the earth favored the retention within the earth-body of the stable crystalline compounds and the elimination of the unstable and mobile. It may be added that the formation of these stable compounds is favored by the conditions that lead to the eliminative process. These conditions were brought to bear on any given matter added to the earth first at shallow depths under moderate temperatures and pressures, and then successively at greater and greater depths, with higher pressures and temperatures, attended by the appropriate eliminations of unstable matter. This progressive action is held to distinctly favor the more and more perfect evolution of a crystalline earth-body progressively growing freer and freer of gaseous, liquefying, viscous, and colloidal elements.

Now crystals are the very type of elastico-rigid bodies. The permanent retention of their specific forms by means of definite elastico-rigid properties is one of their supreme qualities. We are not aware that there is any evidence that a crystal of rock undergoes any plastic or viscous deformation by reason of its own gravity in any known length of time. It may undergo change of form by molecular liquefaction and regelation or recrystallization, but it seems safe to challenge the citation of cases where crystals standing out from their attachments to the walls of crevices or cavities, though athwart the pull of gravity, have shown deflection or deformation, however long they may have stood in this position. The doctrine that flow will take place under gravitative stress if only time enough is allowed seems to be without the sanction of observation in this case, and equally without the sanction of sound theory when the nature of the case is precisely considered. The familiar reasoning is no doubt good for viscous bodies and for bodies in which a quasi-viscous condition can be induced by unbalanced

internal stresses. But in elastic bodies a specific amount of stress is prerequisite. The working tenets for elastic bodies must take account of this. There is a real plasticity and a quasi-plasticity.

The planetesimal hypothesis therefore lends its weightier presumptions to the belief that the earth, or at least its outer mass to great depths, is essentially an aggregate of crystals and derives from them, in a composite form, a measure of their solid elastic properties. The working tenets of this hypothesis are thus normally as distinctly elastico-rigid as are those of the gaseous genus of cosmogonies normally of the viscous type.

It has seemed worth while, therefore, to shape some of the studies in hand so that they will contribute, if they may, to the evolution of the working conceptions appropriate to masses of crystals of earth-dimensions under earth-conditions. Such articles may equally serve the more specific purposes implied by their titles. The discussions now in mind have grown out of studies on formative and on diastrophic processes. Time has changed the order of primacy from the formative of the early ages to the deformative of the later ages, at least it so seems to the student of present problems. We therefore chose the general title "Dia trophism and the Formative Processes" as a thread by which to preserve the semblance of continuity of purpose through the series of articles that may themselves seem more or less heterogeneous. The writer of this word of introduction will not be the sole contributor.

DIASTROPHISM AND THE FORMATIVE PROCESSES. II[1]

SHELF-SEAS AND CERTAIN LIMITATIONS OF DIASTROPHISM

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It will doubtless be agreed at once by all that the general configurations of the oceanic beds are due to deformative processes. There will be a readiness also to agree that the same is true of the beds of some of the seas and minor water bodies. On this background of common opinion we may discuss sea-beds that do not owe their final form to diastrophism but to gradational processes. If all of the former class, large and small, be grouped as diastrophic basins, all of the latter class may be styled gradational basins, however incompletely the term basin represents their forms. There are of course composite and erratic forms that may be neglected here. The most familiar examples of the gradational type are the continental shelves. These are here regarded as only initial forms of the type, falling far short of serving as ideal representatives of the maturest class of sea-shelves. The waters that rest upon these sea-shelves may be known conveniently as shelf-seas.

The ideal shelf-sea is not independent in origin; it is conditioned by the diastrophic sea from which it grows; diastrophism shapes the original basin; gradation superposes certain characters and extensions upon it. These new features are of radical importance in biological and stratigraphical development.

Not only are shelf-seas conditioned at the outset by diastrophism but their histories hang on its continuous or its periodic action. If diastrophism is continuous, the gradational process constantly suffers disturbance and is ineffective; if diastrophism is periodic, gradation goes forward on given lines as long as quiescence continues attaining greater and greater degrees of maturity of type,

[1] This article is nearly identical in substance with a portion of a paper read at the Twelfth International Geological Convention, Toronto, Canada, August 16, 1913.

ceasing only when its systematic work is cut off by renewed diastrophism. If diastrophism is periodic, effective gradational results are inter-periodic products; diastrophism and systematic gradation are alternately dominant. From these general considerations, let us turn to specific features.

The distinctive characteristics of shelf-seas are these:

1. *There is a close approach to parallelism between the surfaces and the bottoms of these seas.* There is but a gentle slope between their landward sides and their seaward sides or their deepest axes. In their immature stages the typical slopes may be 1 in 1,000 or 1 in 800 or steeper; in their maturity the slopes seem often to have fallen to 1 in 2,000 or 3,000 or lower. This close approach to parallelism between surface and bottom is a feature of moment in its bearings on the nature of the deposits and the character of the life.

2. *The parallelism between sea-surface and sea-bottom is close in the further sense that the two planes lie near one another.* For reasons inherent in the gradational processes, the sea-shelf is limited in depth. Beyond a certain depth of water effective transportation of sediment fails, and the further growth of the shelf is checked except as the deep in front is filled. For the limital depth, let us assume 600 feet, 200 meters, 100 fathoms, the recognized mean depth of the outer edge of the present continental shelf. Let considerable variations from this be recognized as consistent with the type, but this figure may serve as representative. Exactness in this particular is not material to the purposes of this discussion, for the distinctions to be drawn are so broad that great latitude is permissible without invalidating the arguments built upon them. The natural criterion of the type is that depth at which the agitation of waves, tides, and currents ceases to keep in effective suspension or in rolling condition so much of the terrigenous silts as constitute the larger mass of the earthy matter derived from the land. The extremely fine material that may float long and far with little motion is negligible as it does not build up the bottom on which it falls apace with the more bulky constituents. The shelf is thus a product whose configuration is determined by its own conditions; it is a self-regulated formation; the guiding element in whose genesis is the sea-surface and the agencies that play upon it.

3. *The sea-shelf is definitely correlated with the penetration of solar rays.* This is a relation of biologic moment. As the mode of formation keeps the face of the shelf within a certain distance from the sea-surface, the waters upon it have a rather definite range of illumination. Competent opinion places the larger part of the effective photo-synthetic action within a hundred meters of the surface, while photographic effects vanish at three or four hundred meters. Organisms that depend on insolation, or that live upon those that do, may be assumed to be rarely fossilized at greater depths than these when there is no ground to suspect postmortem transportation. The shelf-sea deposits therefore embrace the sessile photo-synthetic types and their dependencies. Deeper deposits may embrace the pelagic types, but rarely the sessile and quasi-sessile forms. The shelf zone is therefore from the very nature of the case a biologic horizon of the first importance. Its faunas in consequence belong to a distinctive type. The life entrapped in the bed of the shelf-sea is demarked from that caught in the abysmal bed of the ocean.

There is, however, a narrow belt about the borders of diastrophic seas that enjoys photo-vital conditions much the same as the gradational shelves, though the slopes are normally steeper and the life-conditions somewhat more special and precarious in general. A comparison of the relative values of the gradational shelves and the diastrophic belts within the same depth-limits is a critical part of this study and will be taken up presently. It thus appears that the shelf-seas are photobathic zones of special effectiveness, and are, and no doubt always have been, the habitat of a most important type of marine faunas and floras, the class most akin to the life of the land—pre-eminently the class on which the divisions of geologic history have been based, and may best be based still more specifically, so far as these divisions are biologic.

4. It is scarcely more than a reiteration of the last statement in a special form to say that the faunas of the shelf-seas of ancient times were given distinctive aspects by the conditions of insolation, of aeration, of low pressure, and of agitated bottom, all of which were determined by the mode of origin of these seas. These sea-conditions became, therefore, critical factors in the history of

ancient life. The extent and maturity of these seas has been a decisive factor in geologic history.

5. So too it is scarcely more than reiterating the statement that preceded the last to say that the typical sediments of the shelf-seas at all geologic ages were of the types that depend on agitated waters. The sediments were assorted and spread out with notable uniformity, continuity, and exceptional horizontality over wide tracts because of the conditions of formation.

6. *The shelf-seas were spread upon the continental platforms.* Diastrophic sea-basins may be *set in* between continents (Mediterranean, Caribbean, etc.) or be *sunk within* the continental platforms, but the gradational seas lay upon terraces either built out from the upper edge of the continental platforms or cut back on the upper edge of the platforms, or else were flooded forth upon the lower parts of the platforms by the partial filling of the ocean basins with sediment. They were technically epicontinental, while the diastrophic seas were usually intercontinental or intracontinental. Of course shallow diastrophic basins may be so formed as to be in a sense epicontinental, but not in the constructive sense here applied to the sea-shelves, and of course there were composite types not belonging wholly to either class.

7. *Abandoned beds of shelf-seas were transmitted to later periods, sometimes intact, oftener mutilated, and thus became important inheritances.* Diastrophism may affect distant ocean basins, increasing their capacity and drawing off the waters from above a sea-shelf, leaving it intact. The shelf may continue to escape disturbance until the inwash from all the lands of the globe so far fills the common sea-basins as to lift the sea-surface and force the waters to return upon the abandoned sea-shelf, introducing a new period of sedimentation in close conformity to the old one. Oftener the sea-shelf participates in some degree in the deformation, however preponderant it may be in distant regions, for the earth body is a physical unit and great deformations in one quarter are likely to have a greater or less effect in other quarters. The sea-shelf inherited by the following period has usually been warped in some notable measure and the later terrane is somewhat discordant with the earlier one. And yet the gradational work of the earlier period

is an inheritance of great moment. The work of regrading in the later period is relatively light and the later sea-transgression much facilitated. Even when the deformation between the periods is strongly felt within the same continent, it is usually confined to portions of the transgressive plane only and the rest remains available for the next sea advance. For example, the Mid-Ordovician transgression formed a broad shelf covering half America; this was only partially warped on its east border by the Taconic folding, and the transgression of the Mid-Silurian was greatly facilitated by its inheritance from the Ordovician. The Ordovician had received a great inheritance from the Cambrian shelf-work. The work of all these was handed on to still later periods. This leads us to note an additional characteristic.

8. *The work of shelf-seas was cumulative.* This is true also of base-planes, the working copartners of shelf-seas, but not in an equal degree. An uncovered base-plane is constantly affected by disintegration and on any upwarp to destructive erosion against which it has no protection. The shelf-sea work is constructive and on any upwarp is defended by its own deposits. While it suffers, it has resources of resistance. In addition to this, its attitude is conservative and some notable uplift is necessary to expose all its strata to removal. It thus follows that a great sea-shelf once formed usually transmits its results to successive periods, and each of these adds its own extensions. There is thus developed a succession of sea-transgressions recorded by terrane spread upon terrane, making up a series which is continuous until one of the greater diastrophisms cuts the cumulative process short.

9. *The upper faces of the continents are largely the products of the cumulative work of the shelf-seas, though much mutilated by diastrophism and erosion.* It seems safe to say that 80 or 90 per cent of the surface areas of the continents bear some evidence of former shelf-sea work and 70 per cent or more are still mantled by the shelf products, though some notable part of this mantle has lost its original flat attitude. The relatively plane upper face of the continents is to be assigned largely to base-planing and shelf-sea work in which the latter has left the more lasting, if not the greater, product. Shelf-sea work is pre-eminently a process of terracing.

It is a natural result that the continents are pre-eminently the great terraces of the globe. The picture of the continents as essentially terraces wrought upon diastrophic embossments is no doubt the truest that can be formed, and the contest between the diastrophic forces that emboss by protrusion and the gradational forces that terrace by planation and shelf-building, the chief physical battle of geologic history.

Diastrophic limitations.—Let us now consider the degree of competency and of incompetency of diastrophism to produce shallow seas whose deposits and faunas may be comparable in any serious sense with those of the shelf-seas.

If the earth-body were a perfect spheroid of revolution completely adapted to its own conditions, and if the volume of the hydrosphere were essentially what it is today, there would be a perfect parallelism between the sea-surface and the sea-bottom of the universal ocean that would be the inevitable consequence of these conditions, but there would be no sediments of the common kinds nor any life of the more familiar fossil types, but only the pelagic and the abysmal. The picture of such a state of the earth and of such an evolution as might arise from it, if indefinitely prolonged, is as far as possible from that which geologic history really presents at any known age. The actual earth has a deformed surface of such proportions that about one-third is continental protuberance and two-thirds abysmal depression, with connecting slopes between. At present about one-sixth of the continental protuberance is covered by epicontinental seas, and this sixth adjusts the one-third-two-thirds ratio to the more familiar one-fourth-three-fourths ratio of land to water so successfully inculcated by the geographies. It is the one-third-two-thirds ratio of body-protuberance to body-depression that concerns us in deformative studies. In *these* studies the modification imposed by the sea-shelf work is an incident.

These proportions have been taken of course from the present status. If it is suggested that a quite different ratio may have prevailed in early geologic times and that the ratio in the Paleozoic era may have been so far different as to leave little value in this present ratio, it is a ready reply that no special weight is placed on this ratio

as such. It is merely convenient for use in forming a concrete conception of the work of deformation taken in its largest sense. It is my belief, however, that the ratio of protuberance to depression as defined by the sea-level has not radically changed from the beginning of the Paleozoic to the present time, but geologists entertain varying opinions on this point.

It is becoming more and more clear as study proceeds that the great deformations that determine the ocean depressions and the continental protuberances are not mere superficial incidents of the earth's development. One of the latest geodetic inquiries into the distribution of gravity finds that the outer part of the earth in the United States reaches a state of isostatic equilibrium only at a depth of seventy odd miles, even when an extreme hypothesis of the distribution of differences of specific gravity is made the basis of interpretation.[1] If a natural dying away of the differences of specific gravity from the surface downward is made the basis of interpretation, the depth is much increased and may be more than doubled. The geodetic data of India, a land of great deformations, seem to demand much greater depths than the data of America.[2] Considerations that lie in the mechanics of the case strongly support the view that the portion of the earth that is involved in the highest order of deformations is both thick and stiff.

Now in the deforming of a spheroid whose yielding parts are so deep and stiff as to take on and maintain broad inequalities like the continents and oceanic basins, certain mechanical methods are inherent and inevitably express themselves in the resulting configurations; for example, the portions that are most nearly horizontal will in the nature of the case be those at the bottoms of the sags and the tops of the swells. These portions may be nearly tangent to horizontal planes, but the dips of the intervening surfaces will naturally become increasingly greater toward points midway between the swells and sags, or at least somewhere between them. If, therefore, the sea-surface lies at such a position that one-third or

[1] John F. Hayford, "The Figure of the Earth and Isostasy from Measurements in the United States," *U.S. Coast and Geodetic Survey*, Washington, D.C., 1909.

[2] G. S. Burrard, "On the Origin of the Himalaya Mountains, a Consideration of the Geodetic Evidence," *Prof. Paper No. 12, Survey of India*. Calcutta, 1912.

one-fourth or some considerable fraction of the upper portion of the warped surface is above it and a still larger fraction, two-thirds or three-fourths or some such fraction, lies below it, the zone of shallow water will usually cut the warps at points where they have relatively high dips. The area between the water-surface and the shelf-limit in depth will therefore be proportionately small. For a rough illustration, if the average crests of the continental swells be taken at the modest figure of 6,000 feet above sea-level and the average bottoms of the oceanic sags at 18,000 feet below sea-level, the vertical depth of 600 feet spans only one-fortieth of the total range. The value of this fraction has yet to be reduced for the excess of slope of this portion over the mean slope to give the horizontal breadth of the belt really embraced within the shelf-depth. At the present time the extreme range of deformative heights and depths is more than twice that selected as the basis of this illustration.

An inspection of present conditions seems to show that the sea surface so cuts the normal unmodified diastrophic surfaces that an area not more than half that of the present continental shelf would lie between the contours of zero and of 600 feet depth, or perhaps 2.5 per cent of the earth's surface. This differs radically from the broad areas of shallow water that obtained at the climax of the great sea-transgressions in Paleozoic times when from 40 per cent to 50 per cent of the surface of the North American continent was covered, i.e., from 16 to 20 times as much, and more or less comparable portions of other continents were covered in a similar way and at the same time. That these transgressive seas were shallow is implied by the sediments and by the faunas alike.

Various other modes of inspection lead to results of like order. The discrepancy is so great that the elements of the estimate may be liberally changed to cover all legitimate sources of doubt without affecting the general tenor of the results.

If the borders of the continents be thought to be affected by faulting in some special degree, the incompetency of diastrophism to give these nicely adjusted shelves will be emphasized rather than mitigated, for the usual effect of faulting is an increase of the abruptness of the descent from the land to the deep sea.

These facts seem, therefore, to force the serious consideration of the

proposition that the ordinary diastrophism of the earth is not suited to give the shallow-water seas which the geologic record so abundantly presents for interpretation.

If to escape the force of this proposition one indulges the inherited habit of assuming that a flat area from the sea-bottom "might have been" lifted to just the right height or let down from the land area to just the right level for this specific shallow submergence, it is well to note that the right height is only a small fraction of the full range of height involved in deformation and that the chances of the close adjustment required are correspondingly small, and should be correspondingly infrequent as well as irregular in distribution, whereas the actual case presented by the geologic seas is a systematic repetition of this state from period to period, combined with similarity of action in different continents.

If one indulges in the familiar old idea of a slow subsidence to the sea-level and below, he takes refuge in the most plausible of all diastrophic devices for meeting the actual case. In pure theory, a downward diastrophic movement has little advantage over an upward one in meeting the demands of this case. A downward movement is, however, supplemented by gradation. It is commonly assumed in such a case that the deposits build up the sinking area as fast as it descends and thus preserve an adjustment to the sea-surface. Now if the rate of deposition and the rate of subsidence were *inherently correlated with one another* so as to be co-operative in the same phase, such an adjustment would be natural and be often repeated and so meet the requirements of the case to this extent. If, for example, the weighting due to deposition were sufficient to cause proportionate subsidence, the adjustment would be easily and naturally maintained when once made. This would happen if the earth-surface were in free isostatic adjustment to this degree of nicety and the stiffness of the crust offered no effective resistance to continuous warping. On the adjacent land, however, whence the material for the deposit is being taken, the unloading should cause a proportionate rise and the sea transgression be defeated.

If, however, general elevations and subsidences are dependent on differential stresses in the body of a very stiff elastic earth capable

of accumulating strains of high value, the case is very different, for in such case the crust movements are not immediately responsive to loading and unloading. These can induce only a slight elastic strain in the elastic body. No nice adjustment to deposit can be assumed in this case. In my judgment the phenomena of geology and related sciences support this view and are distinctly opposed to a concurrent adjustment to loading and unloading of the degree of nicety required for the assigned work.

A close adjustment in response to loading and unloading seems on first thought to be supported by views of isostasy that have recently been put forth on the basis of elaborate studies of geodetic data,[1] but this seems to me an untenable application of deductions very important in their true implications, for such a degree of pliancy seems entirely inconsistent with the maintenance of the continents even on the basis of complete vertical isostasy, as will appear from considerations offered in a subsequent discussion, for any type of isostasy that is consistent with the existence of the continents and oceanic basins, as they are, *involves great lateral unbalanced stresses.*

The protuberance of the continents and their repeated rejuvenations when worn down can be explained, it would seem, only on the supposition that the mean specific gravity of the continents is lighter than that of the sub-oceanic segments. This is the postulate of isostasy. Pendulum observations confirm it. It is common ground where diverse views meet.

Now the continents are always being denuded by the mechanical action of wind, water, and gravity on the surface, and by the solvent action of water reaching to notable depths. The protuberances are not only being cut away, but are being leached all the time. There is no real weighting of the continent as a whole under normal conditions. The only apparent weighting is due to that fraction of the sediments that lodges somewhere on it in its course to the great deeps. This fraction is gathered chiefly about the edges of the continent and the weighting there is only a fraction of the unloading of the continent as a whole. The continent as such is being constantly lightened, and if it was in previous equilibrium its constant

[1] Hayford, *loc. cit.*

tendency is to rise. If it can be supposed to have been previously lifted beyond the point of equilibrium it would first be reduced to equilibrium, after which rise would follow. The most that is to be rationally assigned to the weight of sediments on the continental borders is a downward bending of the edges while the adjacent land surface rises under denudation, involving a local tilting of the surface toward the sea. The mechanism thus pictured offers no good ground for the explanation of a great sea-transgression. That the normal tendency of the continents is to rise and has been so throughout geologic history is attested by their continued existence in spite of the constant removal of their material, as also by their periodic rejuvenation and by the continuity of the land life since it began its record. If effective subsidence had habitually co-operated with denudation the disappearance of the continents would have been inevitable. The process of subsidence is not, therefore, normal to the continents. (Subsidence is of course here used in the conventional sense, subsidence relative to the mean earth surface. The mean surface itself may of course approach the center without affecting this relation.) Local or regional subsidence occasionally akes place, but for the continents it is exceptional rather than normal. Apparent subsidence is a common phenomenon arising from the filling of the oceanic basins and the lifting of the sea-level. Local subsidence, as one of the features of warping and faulting, is of course presumed to be nearly as common as the warping itself, but it is of course connected with a complementary uplift. Subsidences of these local types are not tributary to the parallelism and wide extension of the great marine deposits nor to the life adaptations of the great transgressive seas. The consistent elucidation of these constitutes the supreme problem of the geologic seas.

There seem therefore to be very cogent reasons for abandoning the traditional view that the systematic sedimentations and the systematic evolutions of faunas of the higher order are to be assigned directly to vertical or epeirogenic movements of the earth's crust.

OVERTHRUST FAULT IN NEARLY FLAT STRATA[1]

G. SHERBURNE ROGERS

During the past summer the writer in the course of an examination of a part of the ceded lands of the Crow Indian Reservation, Montana, for the United States Geological Survey, discovered a small overthrust fault in nearly flat strata. The following brief description has been written, not only because of this peculiar occurrence of the fault, but because of the extraordinarily clear and almost diagrammatic condition of its outcrop, giving the photograph a possible value for the purposes of textbook or other illustration.

The fault is located in the N.E. $\frac{1}{4}$ S.W. $\frac{1}{4}$ sec. 3, T. 2 N., R. 35 E., P.M., Montana, a point about 10 miles east of the Bighorn River and about 15 miles south of its junction with the Yellowstone. The district is on the remote edge of the Bighorn uplift, the Bighorn Mountains lying about 70 miles away, somewhat to the west of south. About 15 miles southwest of the fault in T. 1 N., Rs. 33 and 34 E., the strata dip in a general northeasterly direction at angles ranging up to 35 degrees. This dip, however, decreases in a short distance, and within a radius of about 10 miles around the fault the rocks commonly lie at angles less than one degree, except for 500 feet immediately around it where the dips locally reach five or six degrees. About 20 miles to the north the strata dip uniformly from three to five degrees in a southerly direction so that the greater part of the area examined occupies the hollow of a broad, flat asymmetrical syncline, the fault being located nearer the southern and more steeply dipping limb. Faults are not uncommon in this area, but all of the other faults appear to be normal and none was observed within 4 miles of the small overthrust in question.

The general relations of the fault, which outcrops in the north bank of the coulee, are shown in Fig. 1. The heavy black stratum is a coal bed, the dislocation of which furnishes the key to the amount of displacement and the position of the fault zone. This

[1] Published by permission of the Director, U.S. Geological Survey.

zone may be seen in the photograph to extend to the left (westward) from near the position of the hammer. It dips 29 degrees east between the ends of the dislocated coal bed but flattens to the west.

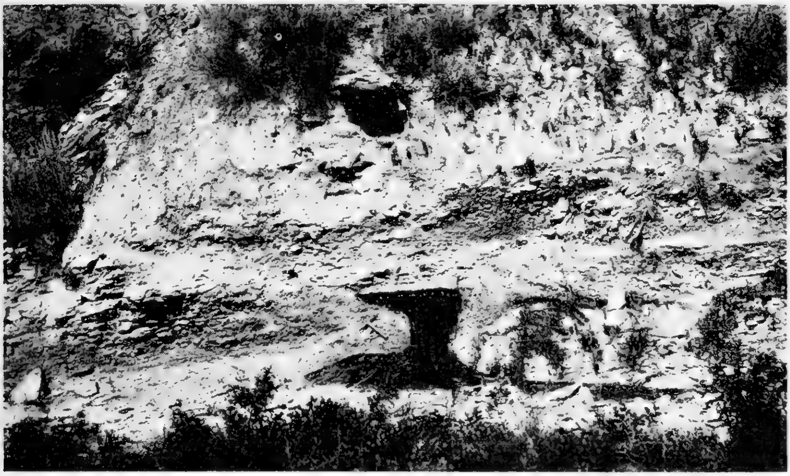

FIG. 1.—Overthrust fault cutting coal bed, sec. 3, T. 2 N., R. 35 E., P.M. Montana.

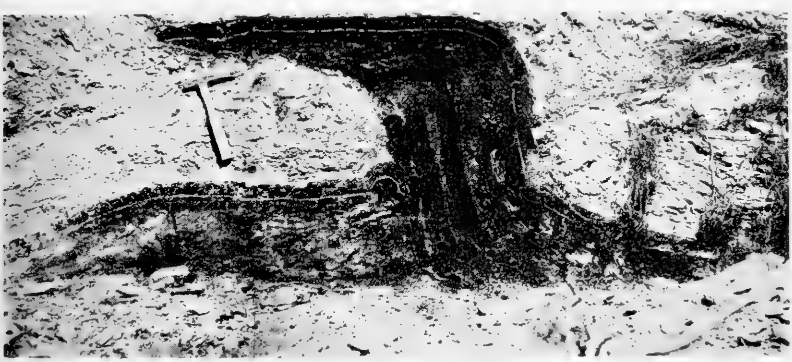

FIG. 2.—Nearer view of fault shown in Fig. 1

The peculiar shape in which the coal bed has been thrown also seems to indicate that the fault zone is not a plane but is curved near the place where it cuts the coal bed. The inclosing strata are

shale, with some sandstone, belonging to the Lance formation and overlain (see upper right-hand portion of Fig. 1) by alluvium. Fig. 2 is a nearer view of the coal bed, which is 16 inches thick, and contains a white clay parting which forms an excellent indicator of the exact character of the deformation. The total displacement is 29 inches.

The fault plane strikes north 15 degrees west. The nearest exposures along this line in either direction are about half a mile away and no trace of the fault can be found except at the locality described.

The thrust seems to have been from the northeast, i.e., toward the Bighorn Mountains. As stated above, it would seem that this fault is connected with the Bighorn uplift, but since there are very few, if any, thrust faults on the eastern slope of these mountains, and since comparatively little is known of the geology between the two localities, it is perhaps unwise to speculate on the tectonic relations of this small overthrust. A feature of greater interest is its occurrence in nearly flat strata, since overthrusting is commonly believed to be a characteristic of, and practically confined to, steeply dipping rocks. In most of the few published descriptions of apparent overthrust faults in flat-lying rocks the writers appear inclined to regard the dislocation as due in some cases to mere local squeezing, probably incident to the settling and adjustment of clay or other soft rock, or in other cases to the slight tilting of a normally faulted block.[1] In the present instance, however, the fault zone may be traced to the top of the cliff, a distance of about 35 feet across the strata, which include several thin sandstones. There seems little doubt as to its true overthrust character.

[1] The case noted by T. E. Savage in "The Geology of the Herrin Quadrangle," *Bull. Illinois State Survey*, No. 16, 1909, p. 279, may, however, be a true overthrust.

CONTRAPOSED SHORELINES[1]

CHARLES H. CLAPP
Geological Survey of Canada, Ottawa

When a shoreline which has been cut in a soft mantle covering hard rocks is, through the complete retrogression of the mantle, placed against the hard rocks, it changes radically, since it becomes dependent on the character of the hard rock surface which was covered by the soft mantle. The development of this type of shoreline is analogous to the development of superposed valleys, and in referring to the type it is desirable to use some term that shall suggest this analogy. The simplest and most evident seems to be the term contraposed,[2] meaning placed against (superposed meaning placed upon).

By the development of a contraposed shoreline, a shoreline may change during a single cycle from mature to youthful. Early in the cycle when the shoreline is cut in the soft mantle it must be simple, nearly straight, and cliffed, submature to mature. As retrogression proceeds the soft mantle is pushed back to the hard rocks and gradually, since the hard rocks are more resistant, is retrograded beyond them. At such a point in the cycle the shoreline is entirely in the hard rock. Hence it is identical to one developed by the depression of a hard rock surface, and is consequently in a youthful stage.

The accompanying block diagram illustrates three stages in the development of a contraposed shoreline. The far block indicates the conditions existing during the early part of the cycle, when the shoreline is cut in the soft mantle. The middle block indicates the conditions when the mantle is retrograded in places beyond the hard

[1] Published with the permission of the Director of the Geological Survey of Canada. Acknowledgment is due Professors W. M. Davis and D. W. Johnson who suggested that I devise a name for the type of shoreline described.

[2] As superimposed has recently and conveniently been contracted to superposed, contraposed is preferable to contraimposed.

rocks. The front block illustrates the conditions existing after the complete retrogression of the soft mantle.

Near Victoria, British Columbia, the development of contraposed shorelines may be seen in all stages, and a short description of them will be pertinent to the introduction of the term contraposed. Apparently the depression and subsequent partial recovery of the submaturely glaciated and drift-covered crystalline rock lowland of southeastern Vancouver Island initiated the present marine cycle. The initial shoreline must have been rather simple, with smooth

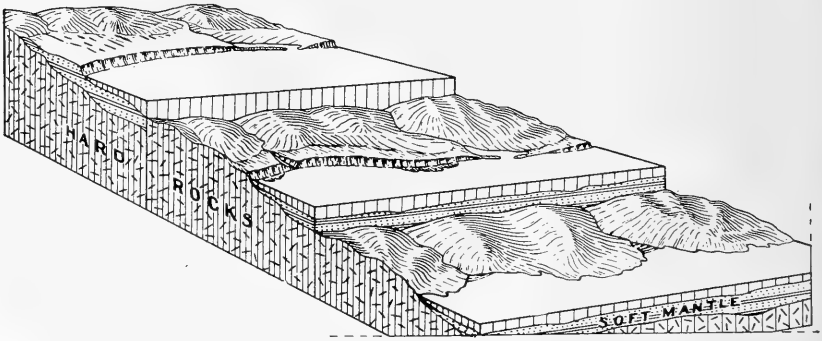

FIG. 1.—Block diagram illustrating the development of a contraposed shoreline

flowing outlines where the crystalline rocks were drift covered, but in a few places where the glaciated rock surfaces were not drift covered, it must have been characterized by many small rounded and smoothed irregularities.

During the present marine cycle the shore has been subjected to moderately strong erosion and the uplifted drift deposits have been rapidly retrograded to form sea-cliffs 200 to 250 feet high with sandpits and bars, and in places, as on the west shore of Royal Roads (see Fig. 2), a nearly straight, mature shoreline. In many instances as along the shore south of Victoria, the drift has been retrograded in places beyond the underlying crystalline rocks. These form small sub-sharp to rounded points, which project beyond the even-cliffed shoreline, the drift-cliff now occurring a few feet or yards back of high-water mark (see Fig. 3). In still other instances, as on the shore of Esquimalt peninsula (see Fig. 2), the

drift has been completely retrograded and the result is a very young, contraposed shoreline. Hardly any of the initial irregularities have been destroyed. On the contrary in the sheared zones, dikes, and interbedded softer rocks small coves and wave-chasms have been cut. The hard rocks themselves have not been beached, but since

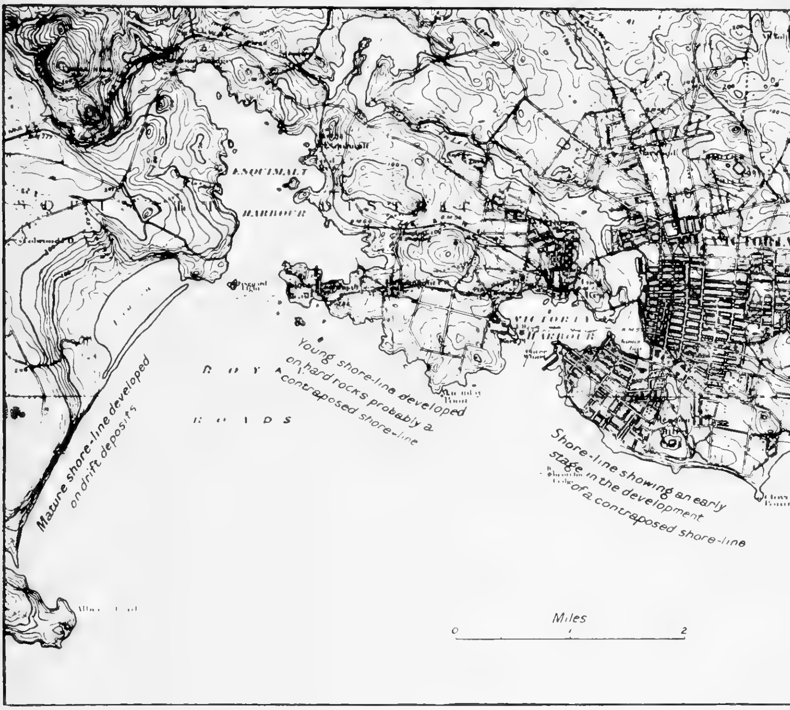

FIG. 2.—Part of the Victoria topographic sheet, Geological Survey of Canada

the retrograded drift deposits frequently occur between headlands of hard rock, there are narrow beaches composed of their material in the protected places of the headlands.

It has been objected to the term contraposed, that it could not be applied on a large scale, that is, that contraposed shorelines would always be very limited in extent. This is more or less true; although one can imagine an extensive contraposed shoreline formed by the retrogression of an extensive coastal plain deposit back to the

older and presumably harder rocks on which the coastal plain deposits were laid down. There are, however, no mapped, good and clear examples of such a shoreline, although much of the Pacific shoreline of North America from Vancouver Island south, may be of this character, since even where the shoreline is cut almost entirely in hard rocks, there are remnant patches of coastal plain deposits; while between the stretches of rocky shoreline are long

FIG. 3.—Contraposed shoreline, showing hard rocks overlain by retrograded soft mantle. Shore south of Victoria, British Columbia.

reaches of mature shoreline cut in extensive coastal plain deposits. The development of the Pacific Coast shoreline has, however, been complex, while the development of an ideal contraposed shoreline is simple, taking place during a single cycle, during which there is, of course, a still stand of the land. But on a relatively small scale, contraposed shorelines are so very frequent in occurrence and so strongly marked and easily recognized, that some generally accepted term for them will be a great convenience.

THE BEARING OF PROGRESSIVE INCREASE OF VISCOSITY DURING INTRUSION ON THE FORM OF LACCOLITHS

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The attention of geologists has been called on several occasions to the laccolithic intrusive bodies of the northern Black Hills, South Dakota. Russell[2] has described and offered explanations for a number of the phenomena there observed. Jaggar and Howe[3] have published a detailed account of the region and performed experiments illustrating the processes which are believed to have led to the formation of laccolithic intrusive bodies; and others have commented on the work of these men, in discussing other regions where similar phenomena may be observed. The classic work of Gilbert[4] and the equally careful studies of Pirsson and Weed,[5] Cross,[6] and others have contributed to placing the theory of laccolithic intrusion on a firm basis. The type of laccolithic structure about to be described has certain peculiarities, to explain which the writer resorted to speculation and came to conclusions for which he later found partial support in the accounts of earlier writers, particularly Pirsson. In the case in point the process which is invoked as an

[1] Published with the permission of the Director of the United Stated Geological Survey.

[2] Israel C. Russell, "Igneous Intrusions in the Neighborhood of the Black Hills of Dakota," *Jour. Geol.*, IV (1896), 23–43.

[3] T. A. Jaggar, Jr., *The Laccoliths of the Black Hills;* Ernest Howe, "A Chapter on Experiments Illustrating Intrusion and Erosion," *Twenty-first Ann. Rept. U.S. Geol. Survey*, Pt. 3 (1901), pp. 165–303.

[4] G. K. Gilbert, "Geology of the Henry Mountains," *U.S. Geographical and Geological Survey of the Rocky Mountains Region*, 1880.

[5] W. H. Weed and L. V. Pirsson, "Geology and Mineral Resources of Judith Mountains of Montana," *Eighteenth Ann. Rept. U.S. Geol. Survey*, Pt. 3 (1898), pp. 445–614.

[6] Whitman Cross, "The Laccolitic Mountain Groups of Colorado, Utah, and Arizona," *Fourteenth Ann. Rept. U.S. Geol. Survey*, Pt. 2 (1892–93), pp. 165–258.

important factor in determining the form of certain laccoliths—increasing viscosity during intrusion—is believed to have been carried to its ultimate results. Since this phase of the discussion has not been presented before in a connected way, the writer hopes the following notes may be of interest.

Near the northwest corner of Spearfish quadrangle in the Black Hills of South Dakota, Crow Peak reaches an elevation of 5,785 ft. This peak is the crowning point of a rugged, sharply dissected, isolated mountain about $1\frac{1}{2}$ miles long and a mile wide, its larger dimension lying north-northwest.

The mountain owes its presence to an intrusive mass of quartz monzonite porphyry. This porphyry outcrops as an elliptical area with its longer diameter (about a mile) trending north-northwest. Where the porphyry breaks through the overlying sedimentary rocks the strata have been bent sharply upward and steep dips (up to 90°) are found at all points on the periphery of the intrusion. These dips become much gentler a short distance from the intrusion and within a half-mile or less the beds have assumed the nearly horizontal attitude prevalent over this region.

There is strong presumptive evidence, however, that the igneous mass has a tongue-like extension northwestward beneath the sedimentary rocks, for the axis of a clearly defined anticline extends in this direction for several miles from the base of the mountain. Such an extension is not indicated to the southward.

The sedimentary rocks involved at this place rest upon a pre-Cambrian basement and are as follows: Cambrian quartzite, sandstone, and shale (Deadwood formation), almost invariably a thin shale at the top above a thin quartzite, 400 ft. ±; Ordovician limestone (Whitewood), 80 ft. ±; Carboniferous: shaly Englewood limestone at base 30 ft. ±; overlain by Pahasapa limestone, 550 ft. ±; succeeded by Minnelusa sandstone, 400 ft. ±; in all 1,460 ft. ±.

A conception of the mechanics of the intrusion must be in large part based upon speculation, for data are not at hand even to definitely establish the underground form of this igneous mass. As may be seen on the map (see Fig. 1), the northern half of the intrusion cuts as high in the sedimentary beds as the base of the

Whitewood limestone. Lowest Cambrian strata are reported by Jaggar, in a tunnel, on the north end of the mountain.[1] On most of the southern half of the porphyry, however, the intrusion reaches the Pahasapa limestone, while at the extreme southern end the Minnelusa sandstone is cut by the igneous rock. Near this latter locality a small mass of Cambrian sandstone was observed, so situ-

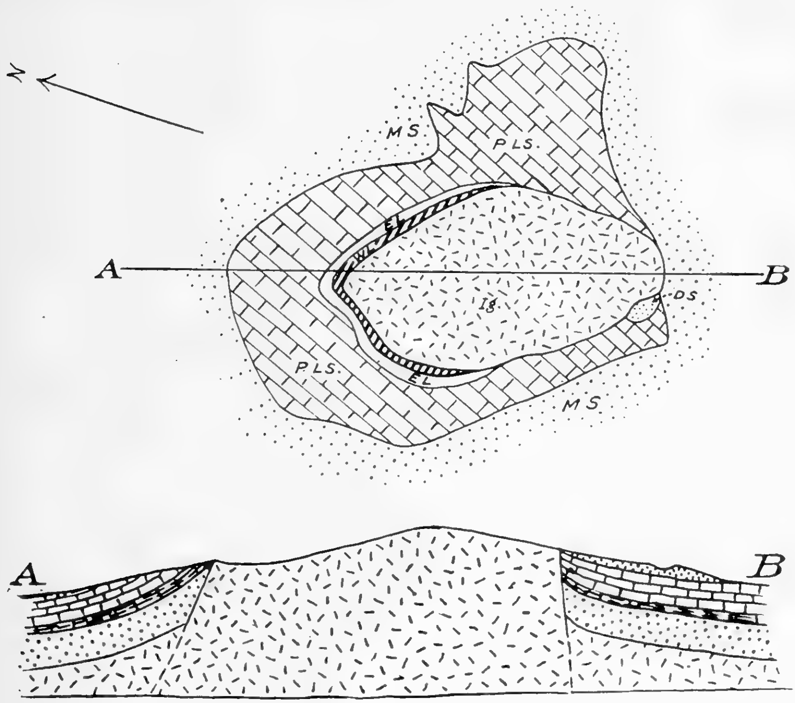


FIG. 1.—Geologic map and cross-section of Crow Peak (Paige): DS, sandstone of Deadwood formation; WL, Whitewood limestone; EL, Englewood limestone; PLS, Pahasapa limestone; MS, Minnelusa sandstone.

ated that only faulting could explain its presence. As figured by Jaggar, both in plan and in cross-section the impression is given that this mass is a symmetrical laccolith either within the Deadwood formation or between the Deadwood and the underlying schists. The cross-section especially suggests that the sedimentary

[1] T. A. Jaggar, Jr., "The Laccoliths of the Black Hills," *Twenty-first Ann. Rept. U.S. Geol. Survey*, Pt. 3 (1901), p. 242.

strata once passed unbroken over a steep dome. In fact, Jaggar refers to this mountain as a type of steep-dome laccolith.

The facts presented above (Fig. 1) show that this is not strictly the case. The intrusive evidently cross-cuts much of the Cambrian section at the northern end of the porphyry, while at the southern end even the Whitewood, Englewood, and Pahasapa limestones are transected. The presence of a small mass of Cambrian sandstone lying against the porphyry on the one hand and the Minnelusa sandstone on the other hand adds weight to this idea that the magma violently forced its way through this portion of the overlying strata much as a punch might perforate plastic material. It is probable that such evidence of violent dislocation decidedly influenced the conclusions of Russell when he termed these masses igneous plugs. Considerations which take into account, however, the configuration of a great number of intrusive bodies in this region, and an examination of the surface structure in the region about Crow Peak leave little ground for supposing that this Crow Peak uplift is different in its broad essentials from these other laccolithic bodies, and it only remains, therefore, to discuss and offer a plausible explanation for its difference in detail, that is, the evidently violent rupture of its summit and the particular curve which the dips of the sedimentary cover would indicate that the magma possesses beneath its covering strata.

It is of interest first to call attention to a fundamental difference in the character of the curve on the upper surface or flanks of the Henry Mountains laccoliths and that on many of the Judith Mountain laccoliths, Montana. Pirsson[1] has noted this difference but does not comment upon it at length. The ideal cross-section of the laccoliths of Mount Holmes[2] (see Fig. 2) as drawn by Gilbert after a careful study of the field may be compared with a typical cross-section as drawn by Pirsson[3] (see Fig. 3) of Judith Mountain. While the cross-section of the upper surface as pictured by Gilbert is everywhere convex upward, that pictured by Pirsson is locally very straight or slightly concave upward.

[1] *Op. cit.*, p. 580.

[2] Opposite p. 28.

[3] *Op. cit.*, Plate LXXXII, section A.–A.

The writer in seeking an explanation for the condition at Crow Peak, and led by the result of one of Howe's experiments in artificial laccolith building,[1] formulated the hypothesis that the form of the upper surface of a laccolith might be materially affected by the progressive increase in viscosity of the magma during injection.

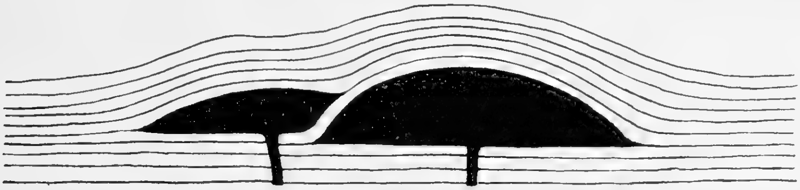


FIG. 2.—Ideal cross-section of the laccolites of Mt. Holmes (after Gilbert)

It was postulated that due to pressure from beneath, magma in fluid condition was introduced at the base of a sub-horizontal sedimentary series, and insinuated itself along the basal contact forming a thin sill or sheet of roughly circular outline. Such a sheet would exert hydrostatic pressure, which if sufficiently great to

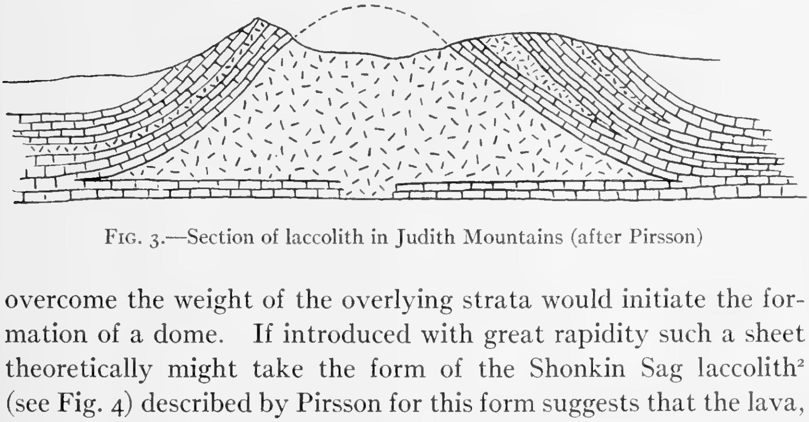


FIG. 3.—Section of laccolith in Judith Mountains (after Pirsson)

overcome the weight of the overlying strata would initiate the formation of a dome. If introduced with great rapidity such a sheet theoretically might take the form of the Shonkin Sag laccolith[2] (see Fig. 4) described by Pirsson for this form suggests that the lava, being introduced rapidly in a thin sheet, attained eventually an area over which the hydrostatic pressure was sufficiently great

[1] *Op. cit.*, experiment III.

[2] W. H. Weed and H. V. Pirsson, "Geology of the Shonkin Sag and Palisade Butte Laccoliths in the Highwood Mountains of Montana," *Am. Jour. Sci.*, 4th series, XII, 1–17.

suddenly to lift the cylindrical mass of rock above it. Pirsson reaches the conclusion that this magma was introduced rapidly, but on other grounds.[1] He says: "The occurrence of ball-like masses in the upper crust of the laccolith seems to show that the filling took place with considerable rapidity." If now it be conceived that magma was introduced more slowly or that its viscosity was greater, thereby interfering with the operation of the law of hydrostatic pressure, the factor of marginal cooling with concomitant increasing viscosity becomes a factor of importance.

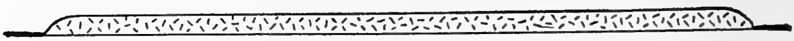


FIG. 4.—Cross-section of Shonkin Sag laccolith (after Pirsson)

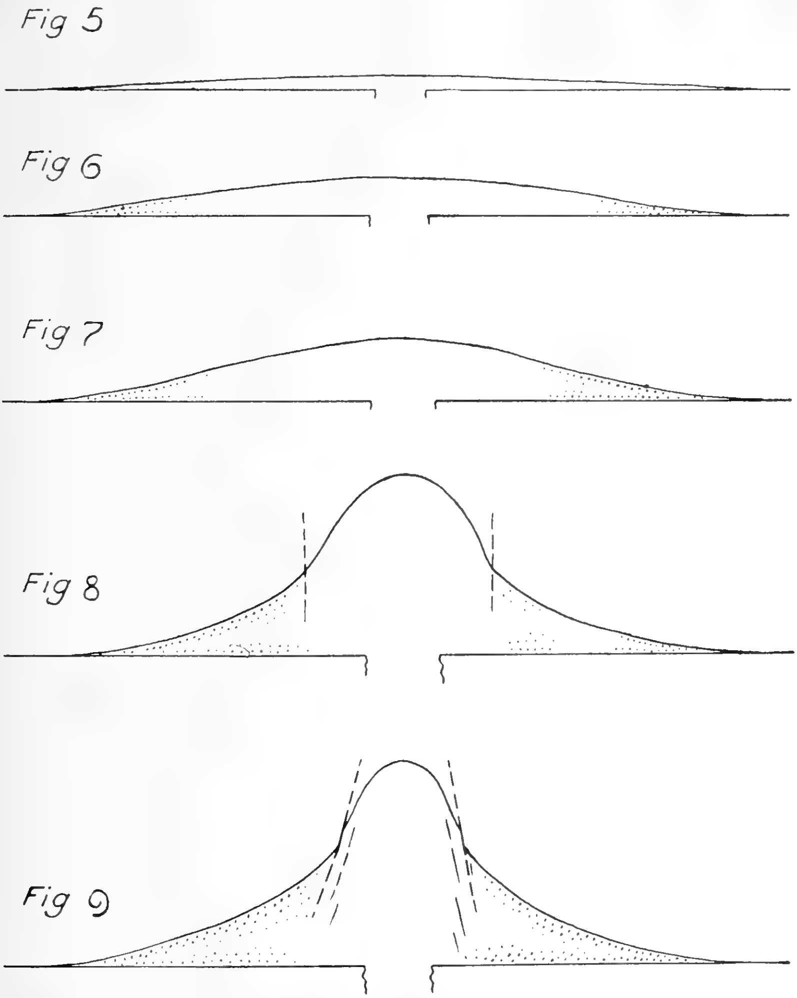
For just as much as the law of hydrostatic pressure is prevented from acting or forced to act more slowly, just so much will there be unequal distribution of upward pressure. The region of greatest pressure will be where the magma is most fluid, i.e., directly over the source of supply, while from this region outward, decreasing pressure will be exerted on the roof. The series of diagrams (Figs. 5–9) illustrate what might take place during intrusion under such conditions. The outer border congealing first, the area of perfectly transmitted pressure would be reduced, and each successive[2] application of pressure would therefore serve to accentuate the upward curve of the strata, that is, the curve on the surface of the laccolithic flanks in such a system would be more or less concave upward.

At one end of the series, then, we would have the Shonkin Sag type with a flat top; under condition of intermediate viscosity the type depicted by Gilbert (where the progressive increase of viscosity was not sufficient to form a curve concave upward, though sufficient to prevent a flat roof); and at the other extreme the type which the Judith Mountain masses approach and which Crow Peak may possess in even greater perfection.

[1] *Op. cit.*, p. 12.

[2] The process was probably continuous in its effect but successive steps are used to express more clearly the idea.

If now this system be carried to its ultimate end what will result? Obviously the dips of the sedimentary strata will approach



FIGS. 5–9.—Series of diagrams illustrating the effect of marginal cooling and increasing viscosity on the curve of a laccolithic surface.

the vertical, and if the central portion of the igneous mass is still competent to transmit pressure either by hydrostatic means or by direct thrust through a central core now become very viscous, it

is quite possible that breaks will occur and their configuration will be more or less circular—the fault surface more or less cylindrical.

It is this end which is believed to have been reached at Crow Peak. In this connection attention is again directed to the horizon against which much of the intrusion now rests, viz., soft shale of the Deadwood formation, and to the small fragment of sandstone of the Deadwood formation faulted against Minnelusa sandstone at the southern end of the intrusive mass. The shale of the Deadwood formation would form an ideal locus for such a break as is hypothesized after the beds had assumed high dips; and the block of sandstone of the Deadwood formation may well represent material dragged up along a fault plane.

Iddings says:[1]

> But when vertical displacement with faulting is one of the chief characteristics of the intrusion a distinction from normal laccolithic intrusion should be recognized. In the extreme this would result in the forcing upward of a more or less circular cone or cylinder of rocks which might be driven out at the surface of the earth, not necessarily in a coherent condition, or might be arrested at any stage of such extrusion and so might terminate in a dome of strata resembling the dome over a laccolith. By this mode of intrusion the vertical dimension of the intruded mass becomes still greater as compared with the lateral dimensions, so that its shape is more that of a plug or core.
>
> Such an intruded plug of igneous rock may be termed a bysmalith. There is then a transition from a flat intrusive sheet to a laccolith with lenticular form and from this to a bysmalith with much greater depth and considerable vertical displacement.

Jaggar in commenting on the description of Mount Holmes by Iddings, says:[2] "The sections and the text indicate that the mass described resembles the steep-sided laccoliths of the Black Hills and that it breaks across strata in the manner of a stock."

Before summing up, specific reference should be made to the work of Pirsson. He says:[3]

> It is of interest to note that the convexity of a laccolith is not a necessary function of its depth but of the viscosity of the lava in relation to the other factors; hence laccoliths of various shapes and sizes may be found in the same horizon. We have seen this, from the present work, as occurring in the Judith Mountains.

[1] J. P. Iddings, "Bysmaliths," *Jour. Geol.*, VI (1898), 705.

[2] *Op. cit.*, p. 289.

[3] *Op. cit.*, pp. 585–86.

It also seems evident that the rate of supply, or the time within which the force acts, must have a bearing in this case, and it is imaginable that the upward propulsion of the magma might be so rapid that a small laccolith could be formed where the arch of the strata was such that it was within the limits of plasticity and would tend to maintain itself after the upward force ceased, even though the magma was in an extremely liquid state.

Also, there is with a given source of supply and a given viscosity a certain limit beyond which a lava cannot form a sheet, but, if the supply of material continues, must form a laccolith. For at a certain radial distance from the supply the internal viscosity, assuming even that its ratio remains the same, will check the transmission of pressure and the onward-propelling, splitting force of the lava; but, the supply continuing, the strata must uparch and form a laccolith.

Pirsson recognized other factors in the problem besides that of viscosity, but they have not a direct bearing here. If any contribution is made at this time, it lies in the suggestion of the function of *progressive* increase of viscosity and its effect on form and in suggesting that, though varying end results may seem to be types which at first sight call for separate classification, they are in fact but stages in a process, the underlying forces of which are generically alike. To be precise: If we select Crow Peak as a type which superficially has characteristics of a volcanic plug as hypothesized by Russell (from descriptions of Newton and Winchell), we reach the conclusion that on a laccolith there was developed a form truly pluglike and that faulting is present of a sort fitting well that which circumscribes a bysmalith. And we suggest that such a cycle of phenomena may be in large measure the result of progressive increase of viscosity during the intrusion of a laccolithic mass; and further, that a series with Shonkin Sag at one end, the convex forms of the Henry Mountains in an intermediate portion, and the concave forms of the Judith Mountains at the other end, may be due largely to the same influence.

CROSS-BEDDING IN THE WHITE RIVER FORMATION OF NORTHWESTERN SOUTH DAKOTA

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United States Geological Survey

Rocks of White River (Oligocene) age have been known for many years to constitute numerous isolated buttes and mesas in the northwest corner of South Dakota, but no detailed study of their character and structural relations had been made until 1911, when, during an examination of the lignite area of that country, the writer had occasion to study the relation of the younger rocks to those containing lignite beds.

Todd,[1] in 1895, recognized the White River formation in the Slim Buttes and called attention to the area in the following language:

> 3. Miocene beds, both White River and Loup Fork, with characteristic fossils, have been found overlying wide areas of the Laramie north of the Black Hills, covering quite deeply most of Harding County, with thin outliers over the north half of Butte County and south half of Ewing. In the Short Pine hills and Slim Buttes these deposits exhibit a depth of 200 to 400 feet with characteristic fossil features closely resembling those of the White River region.
>
> 4. An area of disturbance was found in the north half of Slim Buttes in northeast Harding County covering perhaps 20 to 25 square miles. This consists of sharp folds, including the Laramie and White River beds, with throws of perhaps 100 feet and dips of 25 degrees.

It is the purpose of this paper to show that the inclination of beds described above, as well as those exposed at several other localities in the Slim Buttes, is not a true dip due to a dynamic disturbance but is cross-bedding due to the peculiar manner of the accumulation of the White River formation.

White River beds, showing similar inclinations, are well exposed in at least three widely separated localities along the east side of the

[1] J. E. Todd, "Recent Geologic Work in South Dakota," *Am. Geologist,* XVI (1895), 202.

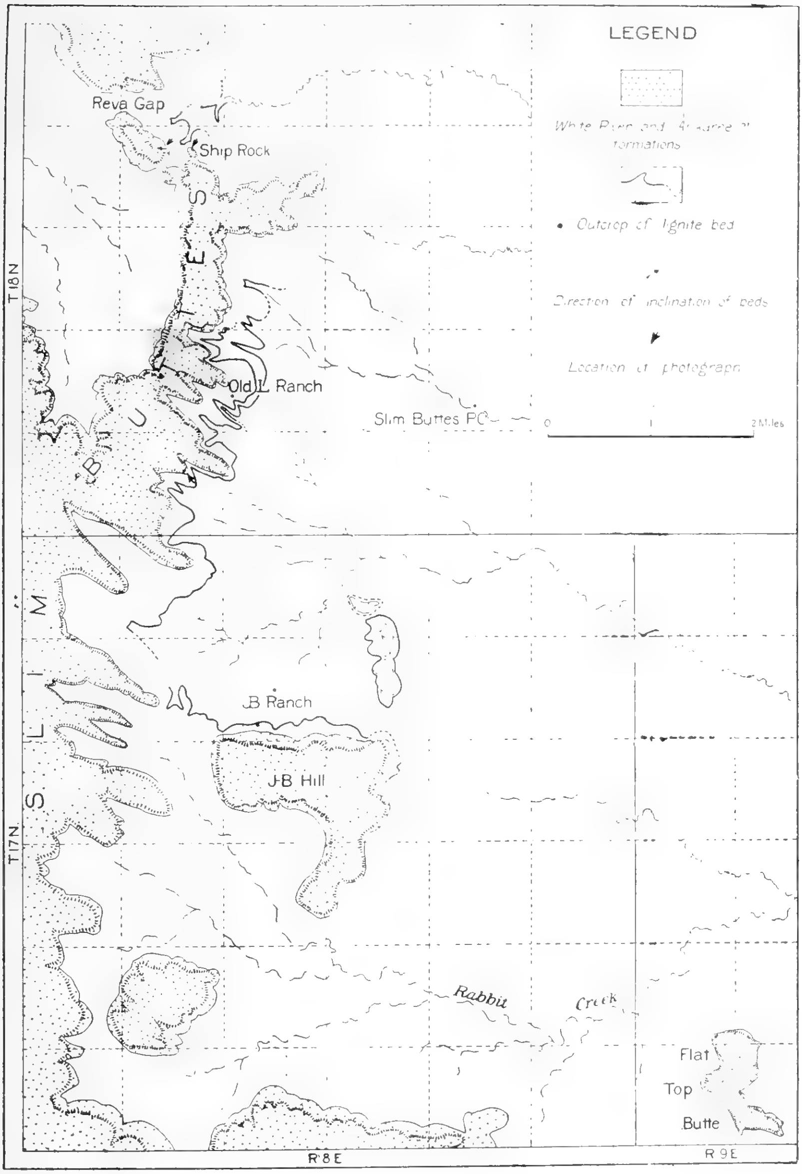

Fig. 1.—Map of part of the Slim Buttes, Harding County, South Dakota

Slim Buttes (Fig. 1): (1) in Reva Gap (Fig. 2), where the inclination is about 30° from the horizontal; (2) one-half mile south of the Old L Ranch (Fig. 4), where the inclination is about the same as in Reva Gap; (3) at the northwest angle of Flat Top Butte, where the inclination of beds is about 20°. In each case the inclined beds are overlain horizontally by a thick, characteristic sandstone, whose age is not definitely known but which has been doubtfully

FIG. 2.—Butte in Reva Gap. Height of cross-bedded portion about 75 feet

referred by Darton[1] to the Arikaree formation (Miocene). The strata beneath this sandstone include clay, marl, and sandstone, as shown in Fig. 3, in which fossils of Oligocene age are abundant. These, in turn, rest unconformably upon the lignite-bearing rocks of the region.

If the inclination of the beds in the White River formation is due to a disturbance of the strata, which occurred at the close of White River time, that inclination should also be evident in the underlying rocks of the immediate vicinity, but such is not the case, as is proven by the following facts:

[1] N. H. Darton, "Geology and Underground Waters of South Dakota," *Water Supply Paper, U.S. Geol. Survey*, No. 227 (1909), p. 21.

1. In the area between Old L Ranch and Flat Top Butte, about seven miles to the southeast, several flat-lying lignite beds are exposed, the outcrop of one (see Fig. 1) having been followed and prospected for a distance of several miles.

2. Between Reva Gap and Old L Ranch, numerous exposures show not only clay and sandstone beds of the White River formation but also the underlying lignite-bearing rocks to occupy a practically horizontal position. Ship Rock (Fig. 3), about 2,000 feet east of the point of which Fig. 1 is a photograph, exhibits White River beds

Fig. 3.—Ship Rock

in a horizontal position below the characteristic sandstone. (Photographs shown in Figs. 2 and 3 are taken looking in a southwest direction.) Hence the inclined beds cannot belong to a single anticlinal structure.

In the study of the lignite beds along the eastern margin of the Slim Buttes, still more convincing evidence was found to disprove the idea that the rocks of the region even in restricted areas were folded and faulted at the close of White River time. As is shown on the map (Fig. 1), a bed of lignite outcrops for several miles along the eastern side of the Slim Buttes in the vicinity of Old L Ranch. This bed occurs only a few feet below the White River formation and its outcrop is well exposed in sec. 32 near the point at which the photograph (Fig. 4) was taken. However,

at no point along its outcrop does the bed show a dip of more than 1°, the maximum inclination of lignite beds of the region, although it is known to outcrop in a canyon north as well as in one south of the high point in which the White River beds show apparent dips of about 30° to the southwest.

On all sides of the Slim Buttes there are large areas of slumped rocks where the attitude of the included beds seems to agree with the apparent dips exhibited in the White River beds which are known

FIG. 4.—Rocky Point, one mile south of Old L Ranch. Height of cross-bedded portion about 100 feet.

to be in place, and it is probable that these slumped rocks have been seen by former geologists and used to substantiate the apparent structure described. One large area of the White River formation, which might easily be used in this respect, is to be found at the north end of the Slim Buttes where sandstone and clay about 125 feet in total thickness, one-half mile in length, and 500 feet in width, occur as a huge landslide now occupying the bottom of a narrow valley. The beds in this block dip 10 to 15° but there is little doubt that the whole mass has moved a considerable distance horizontally, as well as at least 100 feet vertically, from its former position. However, at each of the three localities above described, the cross-bedded White River formation is exposed in the face of

high buttes and is overlain horizontally by the massive Arikaree (?) sandstone which, like the underlying strata, shows no signs of having been disturbed by either landslide or folding.

That the cross-bedding so well exhibited in the Slim Buttes is not uncommon to the White River formation is indicated by the photograph (Fig. 5), taken on Shawnee Creek about nine miles west of Lost Spring, Wyoming. In that vicinity angles of inclination of from 1–22° were observed by the writer on heavy beds of

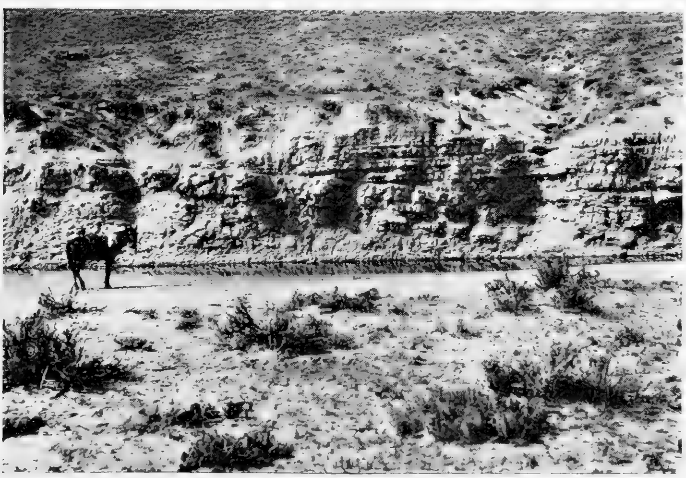

FIG. 5.—Cross-bedded sandstone in White River formation on Shawnee Creek, nine miles west of Lost Spring, Wyoming.

sandstones and conglomerate of White River age,[1] but no conclusive evidence was found suggesting deformation since the White River beds were laid down.

Until recently the rocks of the White River formation were supposed to have been deposited in a vast inland lake which covered portions of Colorado, Kansas, Wyoming, Nebraska, and the Dakotas. As the result of detailed studies, however, it is now believed by many geologists that a portion of the rocks at least were deposited along the flood-plains of shifting streams and perhaps in part by

[1] D. E. Winchester, "The Lost Spring Coal Field, Converse County, Wyo.," *Bull. U.S. Geol. Survey*, No. 471 (1912), p. 479.

wind action. The cross-bedding here described could hardly have been produced in deposits laid down in a large lake, and it requires a vivid imagination to assign it to wind action. Eolian deposits usually exhibit rather minute cross-lamination. On the other hand it is not unreasonable to assign this character of deposits to the action of shifting streams, and in that respect the author is inclined to agree with Hatcher[1] that at least part of the White River formation was accumulated as flood-plain deposits along shifting streams. Darton and others, in southern South Dakota, have been able to trace former river courses along which sandstone phases of the White River formation were deposited, but in the northwestern part of the state the formation occupies only small isolated buttes and it is impossible to trace the old drainage channels along which these remarkable examples of cross-bedding occur, so that definite data along this line cannot be obtained.

[1] J. B. Hatcher, "The Origin of the Oligocene and Miocene Deposits of the Great Plains," *Am. Philos. Soc., Proc.*, XLI (1902), 113–31.

BURIED VALLEY OF SUSQUEHANNA RIVER IN LUZERNE COUNTY, PENNSYLVANIA

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The broad river flats of the Wyoming Valley near Pittston, Wilkes-Barré, and Nanticoke, Pa., are underlain by a deposit of gravel, sand, and clay which is more than 300 feet thick in places. This material occupies a channel which was excavated in the coal measures during early Quaternary time and it is a product of river deposition. Attention was first attracted to this feature many years ago when some of the coal workings reached sand which flowed into the mines in large volume and caused great loss of life.

This buried valley was described by I. C. White in 1883 in his geological report on the region[1] and in 1885 F. A. Hill[2] published additional information regarding it. In the 1885 report[3] also C. A. Ashburner gave a description of the buried valley of Newport Creek. In 1901 William Griffith[4] published a map and view of a model showing the configuration of the floor of these buried valleys based on a compilation of all the borings and other data then available. This map shows the salient features of the valley in an admirable manner, but as numerous areas were not explored by drilling, many portions of it had to be shown hypothetically. Since that time nearly a thousand additional test holes have been sunk by the coal companies, which afford much new light on the configuration of this remarkable trough. Recently in making an examination of the region to ascertain the amount of sand available for filling coal workings I have had occasion to construct a new map, and through the kindness of the coal operators I have been able to utilize all the new data. The result is given in the map (Fig 1), which shows the

[1] Second *Geol. Survey of Pennsylvania, Report*, Vol. G 7, p. 26.

[2] Second *Geol. Survey of Pennsylvania, Report* for 1885, pp. 637–46.

[3] Pp. 627–36.

[4] *Wyoming Hist. and Geol. Soc., Proc.*, VI, 27–36, Plate 1.

salient underground relations excepting in certain relatively small areas, and also shows some minor features, although of course details can be ascertained only where the bore holes are closely placed. The configuration is represented by 50-foot contours with sea-level datum. Where the data are not complete broken lines are used, and in such places the actual contour may differ more or less from that shown. The location of the more significant borings is indicated by dots in order to show the relation of the evidence on which the representation of contour is based. To show all the bore holes would make the map too complex and for this reason also only some of the larger surface features such as river and towns are given.

Glacial features of the region.—The Wyoming Valley region lies well within the area covered by the continental ice sheet of the Glacial epoch. There is a general mantle of till interrupted only by scattered rocky ledges, and the latter show glacial rounding and striation. The striae on the mountains bear to the south but some of those on the lower lands trend to the southwestward, indicating deflection of ice movement down the valley. When the ice was thick this deflection affected only its lower part, but in the earlier and later stages the main flow was greatly influenced by the local topography. This fact was recognized by H. D. Rogers in his later publications on conditions in the region.

The till consists of the usual materials, including many rock masses from the north, and it is predominantly sandy. Some portions are a heterogeneous mixture of sand and clay of bluish tint, carrying many bowlders. It appears extensively along the lower mountain slopes and varies in thickness from 100 feet or more to a very thin veneer and locally it is represented only by scattered bowlders and blocks. In slopes east of Miners Mills and again at a point a half-mile northeast of Alden it presents morainal features with low knolls and pits. Rearranged drift abounds, mostly constituting kame terraces along the sides of the valley. Evidently these were formed when the main valley was partly filled with a lobe of the retreating ice sheet.

Configuration of the buried valley.—The principal features of the buried valley of the Susquehanna are shown on the map (Fig. 1), but there are some characteristics of special interest. It will be noted

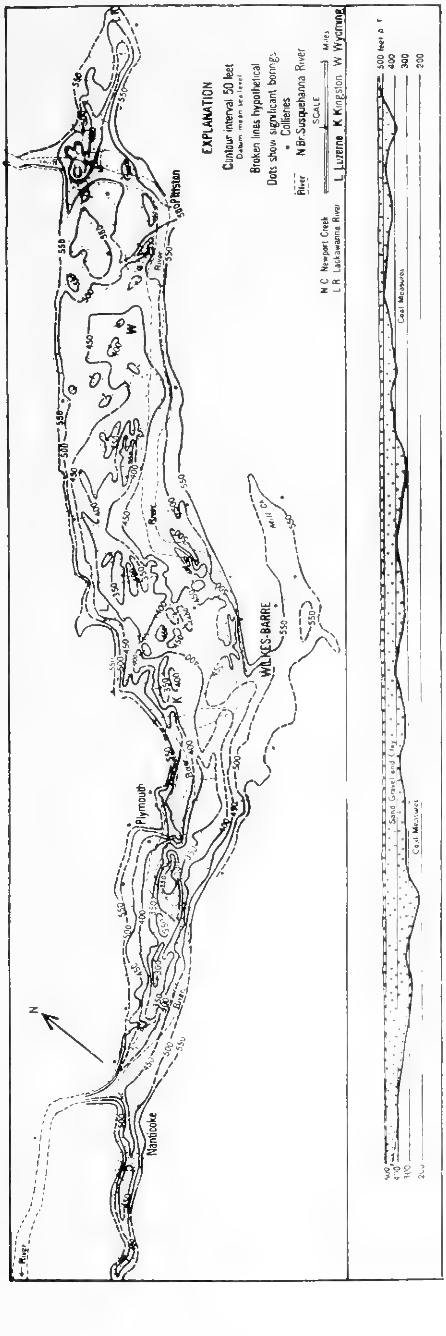

FIG. 1.—Map showing configuration of buried valley of Susquehanna River in Luzerne County, Pa., and section along its deepest portion. By N. H. Darton.

that the underground topography is very uneven and probably if all the details were brought to light much more irregularity of form would be seen. There are long basins and troughs, separated by irregular ridges and saddles, and numerous promontories project from the foot of the adjoining mountain slopes. The rocks are sandstones and shales of the coal measures and of course the excavation was effected by erosion prior to the filling of the valley. As shown on the map and section, the declivity of the underground valley is not like that of the present uniform river grade but there is a succession of irregular troughs. The deepest basin is near Plymouth from which to the southwestward there is a gradual rise of the rock floor as shown by many bore holes across the valley. Recent bore holes on the flats just east of Nanticoke show also that the rock comes to within less than 100 feet of the surface on the south side of the present stream, and as the rock outcrops on the north bank not far away from this group of holes there is no likelihood of a deep channel in the interval. Possibly it may be suggested that there is a narrow canyon cut moderately deep in the rocks here, but a feature of that sort would not be accordant with the topography of the buried channel farther upstream. As noted by previous observers, rock ledges cross the valley at no great distance downstream. The suggestion that some of the deeper basins in the valley are "potholes" is not tenable, for they are too greatly elongated to be in that category.

Materials in the old channel.—The buried channel of the Susquehanna is filled to the level of the present wide valley bottom with gravel, sand, and clay, which, as stated above, reaches a thickness of 309 feet at one place. In general the deposit varies from 100 to 200 feet thick in the greater part of the area. Sand predominates but there is a large amount of silt, or mixed clay and sand, and admixture of gravel in various forms. Some of the gravel is in beds of considerable thickness and extent, but it is generally mixed with much sand. There are many beds of clay intercalated in the deposits, one of them underlying Kingston attaining a thickness of more than 100 feet and extending for some distance up and down the valley. No definite order of strata for any wide area could be determined from the bore-hole records and apparently there is great

variation in the succession from place to place, finer sediments merging into coarser ones in a very irregular manner. There may be considerable till or glacial drift in the valley but it could not be recognized in bore-hole records. Apparently most of the materials have been deposited by the river in part by swift currents and in part in slack water under conditions not very different from present ones at time of freshet when the flats are widely flooded.

The buried channel of Newport Creek.—The deep, narrow, sand-filled basin or trough under Newport Creek valley was described and discussed by Ashburner in 1885[1] and its configuration was shown by Griffith in 1909.[2]

Later borings by the Susquehanna Coal Company have added some very important facts especially as to conditions north of shaft No. 2, where it is found that there is a rapid rise of the floor of the old valley instead of a continuous downgrade as previously supposed. Some of these data are shown in the map (Fig. 1). This valley differs from that of the Susquehanna in containing a relatively wide area of high terrace deposits rising high above the creek.

The deposit in this valley is more than 250 feet thick in places, with its base nearly 150 feet below the bed of the creek and its top constituting a high terrace which originally occupied the entire valley. The greatest width is nearly one-half mile at a point about a half-mile above Nanticoke. Near shaft No. 2 in the northern part of Nanticoke the width of deposit remaining in the valley is only 1,600 feet and the bottom of the buried valley is only 82 feet below the creek bed. The thickness of deposits also diminishes to the southwest but they extend up the valley to beyond Glen Lyon. They thicken locally near this place, for at the Catholic church the depth to bedrock is 109 feet. The material in Newport Creek valley is largely sand with scattered gravel deposits and bowlders, but some portions are so fine grained as to be classed as quicksand.

Mill Creek buried valley.—For much of its course Mill Creek flows in a wide valley that finally merges into the river terrace on which most of Wilkes-Barré is built. Now, however, the creek

[1] *Loc. cit.*

[2] *Loc cit.*

leaves this valley in the northeastern part of the city and reaches the river through a short rocky gorge. The deposits in the old creek valley are nearly 100 feet thick in places, so that their base is considerably below the level of the river. The bottom of this old valley presents considerable irregularity of contour with several deeper basins but bore holes and shafts are too widely scattered to throw much light on the details of topography.

Lackawanna buried valley.—The lower 3 miles of the valley of Lackawanna River are underlain by a buried valley which is confluent with the old valley of the Susquehanna 2 miles above Pittston. This buried valley of the Lackawanna has great declivity, for its channel deepens rapidly and its bottom is more than 150 feet below the present surface in the deep hole at its junction with the buried valley of the Susquehanna. Several basins, branching channels, and other features have been revealed by many bore holes, most of which are shown in FIG. 1.

The origin of the buried valleys.—The history of the buried valleys of Susquehanna River and the other similar features in the same region is somewhat difficult to explain satisfactorily. The channel is not an ordinary valley with continuous declivity, but, as shown by the map and section, it contains elongated rock-rimmed troughs and basins which could not have been eroded by ordinary stream action as suggested by some previous observers. The rock probably is at no great depth below the present river-bed a short distance below Nanticoke, and, even if this is not the case, ledges cross not very far southwest, so the buried valley as a whole is a basin. Deformation of an ordinary river valley since the valley was developed, as suggested by Lyman[1] and Corse,[2] is out of the question, for there are too many small depressions and ridges to be accounted for and the Quaternary deposits along the sides of the present valley show no signs of such disturbance. Probably in early Glacial time the valley was excavated by a river to a grade considerably below the present water level, but the precise depth can only be surmised. The general structure of the Wyoming Valley, a synclinal basin with a thick mass of relatively soft coal measures lying on the harder rocks,

[1] *Philadelphia Acad. Sci. Proc.*, LIV, 507–9.

[2] *Wyoming Hist. and Geol. Soc., Proc.*, VIII, 42–44.

presented a condition very favorable to the development of a feature of this kind. A stream flowing out of the mountains to the north and having sufficiently low outlet to afford declivity could naturally excavate a deep channel along this valley near the axis of the syncline. It could not, however, excavate basins with their bottom materially below its mean grade, that is, there would be no very deep holes in its course. However, when the glacier advanced southward it crossed this valley diagonally and probably picked up a large amount of loose material from its bottom. At this stage and later, subglacial streams also would have had the tendency to deepen basins in the valley bottom. It is believed then that the basins and troughs in the bottom of the old valley were excavated by glacial action largely by the removal of soft and disintegrated material by the ice as it moved across the valley. Later, when the river resumed its flow, large amounts of sand and gravel were carried down the valley and by this means the deeper parts of the old valley were filled to the present level. Apparently there was diminished declivity in this later stage or the river would have re-established the earlier gradient. The filling has continued for a long time and it is now in progress, for deposition is in excess of erosion and at times of great freshets a widespread sheet of mud is laid on the lower lands bordering the river.

The buried valleys of Mill Creek and Newport Creek with their deep holes are to be explained in the same manner as that of the river. Mill Creek has had an interesting history, for not so very long ago, geologically, it emptied into the river on the southwestern part of Wilkes-Barré. This is shown by the continuity of its old valley under the central part of the city. Later it was tapped off by a small stream cutting back through the ridge east of Prospect Colliery and it now flows to the river through a short, rocky gorge.

THE EFFECT OF LEACHING ON DRIFT PEBBLES

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How different rocks endure the superficial agencies of leaching and solution may be seen from the composition of pebbles in bowlder clay where this has been subjected to the solvent action of meteoric waters.

Many years ago the writer took occasion to collect fifty-eight lots of 100 pebbles each, from bowlder clay in Louisa County, in Iowa. By collecting pebbles of one size, about one-half inch, and by taking all of this size to be found on a limited space of the clay surface, unconscious selection of different kinds of rock was avoided. Thirty-seven of these samples were taken from places where the drift was in its original condition, unchanged by subsequent weathering or decay. Twenty-one samples were taken from the upper part of the bowlder clay, where it had been more or less leached and weathered.

In this region the bowlder clay is overlain by loess. The leaching of the clay sometimes extends five feet under the loess, but more often less than this. From this upper part of the till, calcareous material may be partly or entirely absent, so that there is no reaction for carbonates when acid is applied to the clay. Pebbles of limestone, which were no doubt originally present, have wholly or partly disappeared, and only less readily soluble materials remain. The leaching is most complete in the uppermost part of the till, and from here to the unaltered material below, is a zone in which the leaching is incomplete in varying degree. Limestone pebbles in this zone are either etched on the surface, or else they have suffered partial internal solution and are porous and even crumbling and are often yellow or brown from residual or infiltrated ferruginous material.

Below is a table which gives the percentages of the most important rocks noted in the study of the pebble samples collected. In

the first column are the averages of thirty-seven samples of 100 pebbles each, all from till which had not been perceptibly altered. In the second column are the averages of seven samples of 100 pebbles each, taken from somewhat leached till. The third column represents averages of seven similar samples from till somewhat more affected by leaching. The fourth column shows the average percentages for seven similar samples taken from till representing extreme conditions of leaching.

TABLE SHOWING CHANGES CAUSED BY LEACHING, IN PERCENTAGES OF DIFFERENT KINDS OF PEBBLES PRESENT IN BOWLDER CLAY

Kinds of Rocks	1	2	3	4
Flint, chert, jasper (and felsite)	11.2	27.2	45.1	59.0
Vein quartz	7.0	13.5	17.3	21.0
Sandstone and quartzite	4.7	8.0	7.0	8.0
Concretionary hematite	1.0	3.0	1.8	1.0
Granite and gneiss	7.7	11.8	7.7	5.1
Greenstone, schists (and shale)	5.5	7.9	3.7	1.9
Diabase and other volcanic rocks	10.5	15.5	8.6	2.6
Dolomitic limestone	20.10	5.3	2.4	0.2
Calcareous limestone	27.0	5.2	0.5	0.0
Decayed limestone and undetermined rocks	0.5	5.4	3.0	1.7

Under the action of the destructive agencies to which the pebbles of the drift have been exposed in this region, the ratios of the numbers of pebbles of different classes of rocks have undergone progressive changes. These changes indicate that the groups of samples represent successive stages of a general progress of solution. This progress involved a gradual removal of the most soluble rocks. The different kinds of materials are arranged in the table in the order of decreasing resistance to destruction. The end of the process in this case is the removal of practically all pebbles consisting of calcareous limestone. This results in a corresponding increase in the ratios of the numbers of the most resistant pebbles. This increase is greater or less according to the relative resistance of each class of rock.

Beginning with flint, we find that while these pebbles count only about eleven to a hundred in the till that still remains unchanged, they make, in the most thoroughly leached till, 59 per

cent. In one of the seven samples of 100 pebbles of which 59 per cent is an average, there were 70 flint pebbles. In the group of flint were counted a few pebbles of jasper and of a black felsite. Some, which here is called flint, should perhaps have been called chert, which contains some calcareous material. This is present as a mixture throughout the mass of the chert, and in the leached condition of the chert it has been dissolved away, leaving a rock which is a porous silica that readily absorbs water.

Under "vein quartz" were classified the white quartz pebbles which are derived from quartz veins in crystalline rocks, and which themselves have a crystalline structure, although the external crystalline form is hardly ever developed and only very rarely preserved in the pebbles. This form of quartz is somewhat less resistant than flint. While the percentage of flint is more than five times greater in the most leached till than in the unleached, the percentage of vein quartz is only three times as high.

Sandstone and quartzite were classified together for the reason that in the most thoroughly leached till it is often impossible correct y to distinguish the two. In leached quartzite the bond uniting the grains is sometimes weakened and the rock has in effect again become a sandstone. This may lead to the false conclusion that sandstone resists weathering better than does quartzite. Sandstone is, of course, a rock of variable qualities of resistance and strength. The varieties of sandstone and quartzite represented in this drift together are a little less enduring than vein quartz. It appears that they are only about twice as numerous as the vein quartz pebbles in the most thoroughly leached till.

Angular pieces of hematite of variable hardness are present in a small quantity in this till. Sometimes they are in part carbonate of iron. They were originally fragments of clay-iron-stone concretions, which are now mostly changed to iron oxide. Observations on compact hematite pebbles on the plains indicate that these are almost as enduring as flint, but the hematite pebbles in this till suffer somewhat more rapid destruction than sandstone and quartzite and are only about as enduring as granite and gneiss.

At first, the destruction of hematite, granite, gneiss, greenstone, schists, shale, diabase, and other igneous rocks proceeds much

more gradually than does the leaching-away of limestone. In a partially leached till, where some limestone pebbles are still left, the ratios of these rocks to the total are higher than in the unaltered till. In the classes named, gneiss, schists, shale, and volcanic rocks, other than dark diabase or diorite, form unimportant parts of the groups. Basic crystalline rocks evidently resist leaching and weathering less effectually than the acidic rocks.

Dolomitic limestone and calcareous limestone, which occur in about equal quantities in this drift, are both much more promptly removed than any of the other rocks. The ratio of such pebbles to the total is reduced to less than one fourth of its original value before the other rocks have been much affected. In the final stage the ratio of the dolomite pebbles to all others is 1 : 500, and the calcareous limestone has disappeared entirely. A limestone pebble is extremely rare in till, the body of which gives no reaction for carbonate of lime.

These observations show that under the conditions of weathering and leaching in the prevailing climate and drainage of this region, flint is one of the most enduring materials. It is the last thing to yield to solution and general weathering. It is relatively highly insoluble and tough. This explains why flint is a common and large ingredient in the gravel veneer found on the plains and plateaus of the West. It is always an important, and in places almost the only, ingredient in the oldest Pleistocene gravels of the South. The Uvalde formation in Texas consists of gravel consisting almost entirely of flint. About 70 per cent of the gravel taken in the Ohio at Cincinnati consists of flint and quartzite, brought largely from the residual surface material in the upper basin of this stream. Such gravels are also common in some parts of the Pennsylvanian in the central states, and these sediments are known to have been deposited during an era of extensive erosion and hence also general leaching of the land.

REVIEWS

Cambrian Brachiopoda. By CHARLES D. WALCOTT. Monograph of U.S. Geological Survey, No. LI, Part I, Text, pp. 1–872; Part II. Plates pp. 1–363, Plates I–CIV. Washington, 1912.

Rarely, perhaps never, has there been published a paleontological monograph so complete in every detail as this great work on the Cambrian brachiopods by Dr. Walcott. The work is not merely a monograph of the Cambrian brachiopods of North America, but of the Cambrian brachiopods of the world, and it includes also those lower Ordovician species which are close allies of, and doubtless descendants from, the Cambrian forms. The treatment of the fossil forms is both geological and biological. A large amount of geologic and geographic data, of great value to students of geology, is brought together in most convenient tabular form. Many pages are devoted to a record of every locality throughout the world from which Cambrian brachiopods have been secured, giving lists of species, not only of the brachiopods but of other fossil forms which are associated with them, and giving also the stratigraphic relations.

The zoölogical treatment of the fossil organisms is very complete. The various structural details are described with great care. Every line of investigation which gave promise of throwing light upon the relationships of these early forms was assiduously followed, and the results are clearly recorded.

The number of Cambrian species fully described and illustrated in the monograph is 477, with 59 varieties. These are distributed among 44 genera and 15 subgenera, which are grouped under 14 families belonging to the three orders Atremata, Neotremata, and Protremata. The lower Ordovician species discussed are 64 species with 3 varieties, belonging to 14 genera and 3 subgenera, and 6 families. Nearly 77 per cent of the Cambrian species are members of the two inarticulate orders Atremata and Neotremata, and the more specialized order of the articulata, the Telotremata, is not represented. In a survey of this vast array of comparatively simple types of brachiopods, a large proportion of which are of small size, sometimes even minute, many series of which are notably uniform in their general configuration, the astonishing thing is that so great an amount of generic and specific differentiation has been

so successfully determined. The lines of differentiation are shown already to have deployed in many directions in the earliest Cambrian time, and many lines became extinct during the Cambrian.

In order to show the magnitude of the contributions to our knowledge of Cambrian brachiopods during the past few years by Dr. Walcott, it is only necessary to make comparison with the number of forms recorded in earlier works. In Schuchert's *Synopsis of American Fossil Brachiopods*, published in 1897, 116 species and varieties of American Cambrian brachiopods are recorded, while in the present work 474 such forms are described, an increase of over 300 per cent. In the same work by Schuchert the following numbers of species and varieties are recorded from the remaining Paleozoic systems: Ordovician 319; Silurian 311; Devonian 663; Carboniferous 478. These numbers would in all cases be somewhat augmented were a new brachiopod census taken at the present time, but the increase would be in no manner comparable with the 300 per cent increase in our known Cambrian forms. Through the publication of this work of Dr. Walcott the records of the Cambrian brachiopod life are made more complete than for any other geologic period.

S. W.

The Physiography and Geology of the Coastal Plain Province of Virginia. By WILLIAM BULLOCK CLARK and BENJAMIN LEROY MILLER. With chapters on "The Lower Cretaceous," by EDWARD W. BERRY; and "The Economic Geology," by THOMAS LEONARD WATSON. Bull. IV, Virg. Geol. Survey. Pp. 274; pls. 19; 1 map.

A valuable and detailed contribution to the physiography and geology of the Coastal Plain. The formations are minutely described and well illustrated; tables are given containing complete lists of the fossils found together with their geographic and stratigraphic distribution.

The submerged portion of the Coastal Plain is comparatively smooth near the edge of the continental shelf, but nearer land there are numerous small hills with their long diameters roughly parallel to the shore line. The submarine covering near shore consists of fine sands mixed with broken molluscan shells, and local deposits of pebbles and blue mud; farther from shore finer deposits are found. The emerged portion of the plain slopes with gradually decreasing gradient to the shore line. Topo-

graphically it is composed of a set of five terraces designated, from the names of the formations covering them, as Lafayette, Sunderland, Wicomico, Talbot, and Recent.

The upper one, the Lafayette, has a maximum height above sea-level of about 500 feet. It is well preserved in Fairfax County, where it slopes gently to an elevation of about 200 feet and ends at the margin of the Sunderland terrace. The Sunderland terrace penetrates re-entrants into the Lafayette, and the two are, in places, separated by a well-marked scarp line. It is well developed in the central part of the province. Its eastern limit is the 100-foot contour. The Wicomico terrace borders the Sunderland and wraps around it about 20 feet below. From the contact it slopes gradually to the east and terminates at the escarpment representing the west edge of the Talbot terrace. The latter surrounds the Wicomico as a border and is separated from it by a sharp line of cliffs 10 to 20 feet high. The scarp is conspi uous just west of the Dismal Swamp. The eastern limit of the Talbot terrace is either a wave-cut cliff or the modern beach. The Recent terrace is almost wholly submerged.

The oldest series of sediments exposed on the Coastal Plain is the Lower Cretaceous. The lowest member of this series, the Potomac group, was laid down as a mixture of terrestrial, lacustrine, and fluviatile sediments, as indicated by the absence of any strictly marine fossils, and by the presence of estuarine species of shells. The flora is varied and includes equiseta, ferns, cycads, conifers, monocotyledons, and dicotyledons. The exposed thickness of the series in Virginia is about 500 feet, but a recent well at Fortress Monroe has penetrated 1,300 feet, showing an increasing thickness to the east.

The Patuxent beds rest for the most part upon the crystalline rocks of the Piedmont area, but near Doswell they lie upon the Triassic. The outcrops are conspicuous at the head of tide in the main drainage basins. The Arundel formation is not recognized in Virginia. The relation of the Patapsco beds to the Patuxent is one of decided unconformity, and the irregular erosion surface of the Patapsco is emphasized by the marine character of the overlying deposits. These resemble the Patuxent in their varied materials but are, in general, finer. The outcrops are best seen along the Potomac River near Washington.

Upper Cretaceous beds are not exposed in the region, but borings for wells have brought up fossils which have been identified as Upper Cretaceous. The material resembles the Matawan formation of Maryland and New Jersey.

The Eocene representative, which was at first thought to consist of a single formation, and was called the Pamunkey formation, has since been differentiated into two stratigraphical units known as the Pamunkey group. The lower of these, the Aquia, consists of greensands and greensand marls interbedded with occasional shell layers. Locally the beds have been subdivided into zones. The upper member, the Nanjemoy, overlies the Aquia conformably and is composed of greensands, but differs from it in having a greater argillaceous and less calcareous content. The contact is usually represented by a bed of white and pink clay. The combined thickness of the two formations is about 200 feet. The Eocene fauna is dominated by the presence of countless molluscan individuals; a total of 61 gasteropods, 60 pelecypods, and 30 protozoans are recorded. There are also five species of reptiles and eleven of fishes.

Miocene deposits have an extensive outcrop due both to their thickness and to their gentle dip. Four formations are recognized, known as the Chesapeake group. The basal member, the Calvert, rests unconformably upon the Nanjemoy, Aquia, Patuxent, and early crystalline rocks, and consists of fine-grained sands, clays, marls, and diatomaceous earths. Gypsum and glauconite are common in the clay. The width of the outcrop reaches 30 miles and is well shown in the counties of King George, Essex, Caroline, and Hanover. Above the Calvert the St. Mary's formation is present with an unconformity that represents the complete removal of the Choptank member which is present in Maryland. The deposits are similar to the Calvert except that diatomaceous earths are lacking. The upper formation, the Yorktown, is, so far as known, conformable upon the St. Mary's. It is characteristically made up of beds of finely comminuted shells apparently accumulated in shallow water. Layers of clay and sand are also present. The faunas are rich and varied and, on the whole, indicate a marine origin for the Miocene strata.

The Lafayette formation is placed tentatively in the Pliocene. It consists of unconsolidated sands and gravel, and where the deposits have been least eroded the uppermost beds are capped by loam that varies from a few inches to 10 feet in thickness. It is markedly unconformable upon all the underlying formations, and is in contact, at one place or another, with almost every older formation in the region. It is practically unfossiliferous. Its distribution is coextensive with the Lafayette terrace.

The Pleistocene formations are all surface deposits and are, in general, represented by the terraces described in the early pages of the bulletin.

The correlation of the various deposits with those of other regions is cautiously discussed. The Patuxent is correlated with the Trinity of Texas, the Lakota of the Black Hills, the Kootenai of Montana and British Columbia, parts of the Shasta group of the Pacific Coast, the Kome beds of Greenland, and possibly with the Morrison of the Rocky Mountains. The Patapsco is probably of the same age as the Fuson formation of the Black Hills, and parts of the Lower Cretaceous of the Gulf and Pacific coasts. The data are too meager to attempt correlation of Upper cretaceous deposits. The Aquia and Nanjemoy are correlated approximately with the Wilcox and Claiborne of the Gulf region.

E. A. S.

The Mount McKinley Region. By ALFRED H. BROOKS. With Descriptions of the Igneous Rocks and of the Bonnifield and Kantishna Districts by L. M. PRINDLE. Professional Paper 70, U.S.G.S. Pp. 234; Pl. XVIII; Fig. 30.

The field work for the report was done in the summer of 1902. Extreme difficulties were encountered, but in spite of them a distance of 800 miles was covered by the party of seven men in 105 days. Aside from the geological and economic discussions, the report includes a detailed narrative of the trip, a review of previous explorations and surveys, and a valuable statement of the complete equipment.

All rocks older than the Devonian are greatly metamorphosed and include undifferentiated sediments, with some igneous rocks that are thought to be Paleozoic. Rocks that may be still older than these are micaceous, graphitic, and quartz schists that occur in the northeastern part of the Alaska range and in the Yukon-Tanana region. The Ordovician rocks are blue limestones with black carbonaceous argillites, siliceous limestones, and calcareous slates, occurring along the north front of Alaska range. Some green argillites and cherts of 4,000 feet thickness are of uncertain age but are tentatively called Devonian or Silurian. The Devonian is represented by 200 feet of heavy fossiliferous limestone, 2,000 feet of chert, quartz conglomerate, sandstones, and slates, together with some volcanic rocks which may belong to the Carboniferous.

The Mesozoic group is abundantly represented by Lower, Middle, and Upper Jurassic rocks of great variety and thickness. There are remnants of igneous activity at the base and the top of the Jurassic.

The Cretaceous beds are sedimentary and less thick than the preceding ones.

The thickness of the Kenai formation ranges from 150 to 10,000 feet and embraces widely distributed outcrops of conglomerates, sandstones, shales, and coal beds. The last period of diastrophism followed Eocene deposition. Glaciation has been an important factor in the development of the present topography.

Gold and coal are the important resources; bituminous coal is of far more commercial importance than the lignites.

E. A. S.

The Geology of the Greymouth Subdivision, North Westland, New Zealand. By PERCY GATES MORGAN. Bull. 13 (New Series), Geological Survey Branch of the Department of Mines. Pp. 160; pls. 6; figs. 7; maps 8; sections 3.

This area is located along the northwest shore of North Westland and includes about 510 square miles. The oldest rocks are strongly folded argillites and graywackes known as the Greenland series. These are pre-Tertiary in age, no closer correlation being offered. Next younger than these are the coal measures, of probable Eocene age, consisting of sandstones, conglomerates, shales, and mudstones. Some valuable coal seams are also included. Four divisions are recognized: the Paparoa beds of shale and sandstone; the Brunner grits, conglomerates, and sandstones; the Island sandstone; and the Kaita mudstone. It is believed that glaciers existed in the highlands which were furnishing sediments at this time.

Miocene deposits are largely marine, and contain abundant fossils in some localities, so that the age of the rocks is well established. Pliocene exposures are limited. Pleistocene morainic and fluvio-glacial gravels show that a cold climate prevailed at that time. The gravels are everywhere auriferous.

The principal economic resources are the coal beds. The amount of coal in the ground is estimated at 600,000,000 tons, about one-fourth of which is available under present conditions. There are indications of petroleum.

E. A. S.

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Announcement

The University of Chicago Press will publish about October 1 another book by Jacques Loeb. The new work, entitled "Artificial Parthenogenesis and Fertilization," presents the first complete treatment of the subject of artificial parthenogenesis in English. Professor Loeb published four years ago a book in German under the title "Die chemische Entwicklungserregung des tierischen Eies." Mr. W. O. R. King, of the University of Leeds, England, translated the book into English, and the translation has been revised, enlarged, and brought up to date by Professor Loeb. It gives, as the author says in the preface, an account of the various methods by which unfertilized eggs can be caused to develop by physico-chemical means, and the conclusions which can be drawn from them concerning the mechanism by which the spermatozoon induces development. Since the problem of fertilization is intimately connected with so many different problems of physiology and pathology, the bearing of the facts recorded and discussed in the book goes beyond the special problem indicated by the title.

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DIASTROPHISM AND THE FORMATIVE PROCESSES. III

THE LATERAL STRESSES WITHIN THE CONTINENTAL PROTUBERANCES AND THEIR RELATIONS TO CONTINENTAL CREEP AND SEA-TRANSGRESSION

T. C. CHAMBERLIN
University of Chicago

In the second article of this series—preceding number of this *Journal*, pp. 517–33—it was urged that ordinary diastrophism springing from internal stresses is, in its very nature, unsuited to adjust the surface of the earth to the surface of the sea over wide areas with such close nicety as effectively to facilitate the great sea-transgressions and the formation of the great terranes of marine sediments that spring from them. This inadaptability is held to arise chiefly from the fact that the deforming earth-stresses, on the one hand, and the working relations of the sea-surface to the sea-shelves, on the other, are so far independent of one another in origin and mode of action that they are not naturally co-operative in so close and harmonious a way as to be suited to produce the observed results, since these are obviously the effects of nicely adjusted relations.

So, too, it appeared that such vertical stresses as may arise from loading and unloading in the process of gradation are unsuited to produce these results, because loading and unloading tend to produce a warp between the loaded and the unloaded tracts,

whereas great sea-transgressions and great terranes of parallel sediments require either a movement that retains the parallelism of the sea-surface and the sea-bottom, or else the essential absence of any movement at all. A constant upwarping of the land inevitably defeats extensive sea-transgression and its consequent terranes.

In further pursuing the conditions that favor or oppose great sea-transgression and the formation of the great parallel terranes of marine strata, we have now to consider the unbalanced stresses that inevitably arise *within* the continents as a consequence of their own protrusions. These are to be distinguished from the internal stresses of a more general nature that are usually regarded as the cause of orogenic and epeirogenic movements which are here covered by the phrase, ordinary diastrophism. The stresses that arise within the continents simply because they protrude above the ocean beds are of a much more special and limited class. These stresses depend simply on gravity acting on the protruding matter as such without regard to other conditions; they are strictly inevitable and in the main independent. If the base on which the continents rest were absolutely inflexible, lateral stresses would arise within the continents from their gravitative pressures on their own masses, just as such stresses arise in continental glaciers and actuate them. If, on the other hand, the continents floated on a molten interior, or were in any other way kept in a continuous state of isostatic adjustment—in the usual sense of isostasy in which each column equals every other column in radial pressure—there would still arise within the protuberances unbalanced *lateral* stresses in proportion to the degree of protrusion.

It is perhaps necessary to remark here for the sake of complete clearness that isostasy, in the most complete and unlimited sense of the term, involves equal pressures in *all* directions, not merely equal pressures in vertical directions. Equal pressures in all directions are predicable only of perfect fluids. In this radical sense, the earth cannot be in complete isostatic adjustment at the present time because of its inequalities of surface and because of the differences in the lateral distribution of specific gravity in its crust, even if every vertical column balances every other vertical column perfectly. If the earth were ever in a complete

molten state—a view I do not now entertain—it would no doubt have assumed a state in which the lateral pressures would have been strictly equal and the vertical pressures also equal at any given depth, though of course varying with depth. The isostatic conditions would doubtless then have been complete and perfect in this radical sense, if we neglect such modifications as might have arisen from convection and similar internal disturbing activities. There should then have been a closely concentric arrangement of material according to its specific gravity, a uniformly level surface, and a universal ocean of uniform depth, as logically pictured by our geologic forefathers. This beautiful picture, were it true, would seem at first thought greatly to simplify the dynamic and diastrophic problems of the earth body, but in fact it forces upon us at once a problem of grave difficulty, the problem of finding a really rational way in which an earth, starting with such a symmetrical organization, could have passed into an earth with such irregularities of form and substance, and such differentiations of specific gravity as are actually presented by the existing earth. The depth to which the specific gravities of the continents and the sub-oceanic segments have recently been found to differ presents a new and formidable difficulty. The recent revival of the doctrine of isostasy, on the basis of geodetic data,[1] appears to have been regarded in some quarters as lending fresh support to the inherited view of a liquid earth, but in reality the results reached greatly augment a difficulty which had never been met with full success: the mode by which a horizontal differentiation of specific gravity in the outer part of the earth body could take place on a large scale, together with the mode by which the continental swells and the oceanic sags could be initiated and maintained. These great inequalities can be sustained only by adequate powers of resistance to the lateral stresses that tend to equate them and must always have tended to equate them. How such differentiations could have been forced upon a globe once in a fluidal condition—from which these

[1] The "Figure of the Earth and Isostasy from Measurements in the U.S. Coast and Geodetic Survey," Washington, D.C., 1909, and other papers of John F. Hayford; see also G. S. Burrard, "On the Origin of the Himalaya Mountains, a Consideration of the Geodetic Evidence," *Prof. Paper No. 12, Survey of India,* Calcutta, 1912; also *Geol. Mag.* Dec. V, Vol. X, No. 9 (September, 1913), pp. 385–88.

differentiations were necessarily absent—against the great stress-differences involved, is an obdurate problem that now takes on a new and definite aspect because of the very considerable depth to which the differentiation of specific gravity is found to extend. This, however, is not a problem to be discussed here; its solution is the task of those who entertain the view of the former fluency of the earth. The question is serviceable here by way of giving emphasis to the lateral stresses that inevitably exist in a protruding continental body due to its own gravity. If the continents were instantly converted into a molten condition they would flow at once and with violence toward an isostatic state and give a catastrophic illustration of the difference between the present state and a complete isostatic state.

The nature and the intensity of the lateral stresses in the continental protuberances may be easily visualized by means of an analytical picture of the continents and the great basins. Let these be assumed to be in isostatic equilibrium in the limited sense of the term as commonly used and let the protuberances be divided into independent vertical prisms of uniform dimensions. Then, if we choose to take the isostatic flotation view, each prism will float freely at a height inversely proportionate to its specific gravity, assumed to be the present height; or, if we prefer the solid isostatic view, each prism exerts the same pressure as each other prism on its base at the level of compensation. If the prisms be viewed as independent of one another, they must be sustained against the tendency to spread and collapse under their own gravity by a rigid coherent force acting transversely and equal at each point to the gravitative pressure at that point. This pressure is easily computed. If for this purpose we take the very conservative reliefs of 6,000 feet for the summit swells of the continents and of 12,000 feet for the bed of the ocean, the relief-difference will be 18,000 feet. This is not half the extreme actual differences but may perhaps fairly represent the continents if they were reduced to symmetrical swells. If we assume a specific gravity of 2.7 for continental rock, the gravitative pressure of the base of a prism rising from the horizon of the ocean bed to the border of the continents at sea-level, 12,000 feet, would not be far from 14,000 pounds to

the square inch. Over against this would be the pressure of 12,000 feet of water or roundly 5,000 pounds to the square inch, leaving a differential pressure of 9,000 pounds to the square inch, which may be taken as representing the pressure at the base of the border prisms of the continent. The prisms that would form the summits of the continental swells, taken at 6,000 feet above the sea-level, would suffer a differential pressure of about 16,000 pounds per square inch at their bases. Now unbalanced pressures of 9,000 to 16,000 pounds per square inch are equal to the crushing strength of weak rock and approach that of average rock. Oblique or transverse shearing would not unlikely take place in a prism of rock instead of crushing and this would require appreciably less stress, but just how much less has not been well determined as yet, so far as I know. There would be, at any rate, at the base of each such ideal prism of the continents, internal stresses that would approach the average strength of the rock of which they were composed and, in the weaker cases, would probably exceed it.

If now, instead of our idealized continental swells, we take the actual case, the stresses will be found much more intense. For example, the present Tibetan plateau over a wide area has an elevation of 15,000 feet or more above the sea-level, and the ocean bed, not far away, is considerably more than 12,000 feet in depth, so that after allowing for the oceanic pressure, there would be at the base of a Tibetan prism an unbalanced lateral pressure of 25,000 or 30,000 pounds to the square inch. In an isolated column this would be opposed only by the rigidity of the rock, and if this were of the average type, creep would certainly take place in the lower portion, if crushing did not anticipate it. The phenomenon of creep in mines and canyons under much less pressure leaves no room for doubt on this point.

But massed as the ideal prisms actually are in the continents, and surrounded by low slopes running out under the edges of the oceans, the actual case presents a modified aspect. The prisms not only lend some support to one another—though they must then carry one another's burden in some degree—but the sub-marine continental slopes buttress them. These buttresses are subject to lateral pressures of their own, but in so far as these pressures

fall below the creep pressure the residue of the strength of the buttresses opposes continental creep. The sub-oceanic buttressing is subject to further qualifications whose natures are more or less uncertain. The substructure of the border slopes of the continents is unknown. To some geologists, the preferred picture of the continental borders is that of fault scarps with slopes of incoherent sediment banked against these. To others, it is that of warps or folds of indurated rock below with sheets of recent sediments above and banks of recent sediments on their outer borders. To still others, the picture is that of a graduated sedimentary series, soft and incoherent at the surface and on the abysmal face, grading downward and backward into more and more indurated rock. This may or may not be more or less warped and compressed by thrusts from the ocean bed, according to situation. There are no doubt other conceptions. The continental borders present a suggestive field for study which has not yet been adequately cultivated.[1] It would be a diversion from our main purpose to enter into a discussion of the details of the continental borders here, but, though opinions are diverse in other respects, they are at one on two features that bear on this discussion: (1) some notable portion of the border material is soft and feebly coherent, and (2) the borders of the continents have been specially subject to deformative processes throughout geological history and were hence probably weakened in their resisting powers thereby through the development of shear planes. There is good reason to believe also that creep takes place in the more recent soft material, whatever may be true of the indurated parts of the continental protuberance as a whole.[2] These considerations make it difficult to judge how far the buttressing of the continents by the border slopes is effective in resisting the lateral pressure that tends to spread the protruding masses.

There is another consideration that affects the degree of resistance to lateral spreading in a possibly important way. It seems clear from an inspection of the folds of mountains that they are relatively superficial.[3] It is probable that a shear zone has been

[1] For some suggestions see Chamberlin and Salisbury, *Geology*, III (1906), 523–29.

[2] *Ibid.*, pp. 527–28.

[3] *Ibid.*, II, 128.

developed beneath the shell when it has suffered orogenic movements and that this facilitated folding and at the same time tended to limit it below. The shear is probably distributive through some depth and covers the horizons at which the tendency to creep is chiefly felt. The shear planes thus formed by the forceful orogenic agencies may serve as planes of movement for the less forceful creep afterward. The occasion for creep springs in some part from the elevation involved in the folding and allied diastrophic processes, and the creep itself is of the nature of a reversal of the elevating process, and so it may not unnaturally be facilitated by the shear planes already developed by the antecedent diastrophism.

Complicated by these modifying factors whose values are uncertain, it does not appear that the problem of creep is at present susceptible of satisfactory computative treatment; it can be dealt with now only in a naturalistic way on the basis of the evidence and the probabilities of the case. In time, when suitable geodetic surveys shall have been repeated, there will come positive demonstration. The creep movement, if it is appreciable, must result in a spreading of the geodetic stations, and exact measurements after sufficient intervals will give unequivocal evidence of the movement or of its absence, as also of its nature and its rate. Some few first steps in this direction have already been taken; notably the geodetic re-survey of the region of the recent California earthquake. Horizontal strain followed by horizontal movement were there shown, but they were too limited and their interpretation too uncertain to contribute much to the general question of creep. The demonstration that the movement was horizontal is, so far forth, favorable. The recognition that this and certain other earthquakes were due to differential horizontal movements—in distinction from the vertical movements to which earthquakes have generally been referred—is perhaps a step toward the demonstration of a wider system of horizontal movements of secular prevalence.

It would be going too far from our immediate purpose to set forth in full the phenomena that seem to point to glacier-like continental creep as one of the prevailing movements of the earth's crust. We are here merely seeking its possible effects on sea-transgressions and the stratigraphic terranes dependent on these.

The nearly universal presence of gaping crevices over the whole face of the continents, affecting all classes of rocks, is quite in harmony with a general spreading movement and has not otherwise found an altogether satisfactory explanation. Supporting this also is the prevalence of tensional faulting to so great a degree that it has gained the name *normal* faulting.[1]

It can hardly be supposed that such lateral stresses as must exist within the continents from the nature of the case, can fail to produce some effect, since changes of various sorts are going on within the continents, particularly molecular changes stimulated by heat, pressure, and other forces, and these must be influenced by the lines of least resistance imposed by the differential stresses. The vital question is whether this is a matter of geologic consequence or not. We must apparently wait for a decisive answer, and in the meantime treat the possibility of effective creep hypothetically.

The point of special interest in this discussion is the bearing which the hypothetical glacier-like creep of the continents has on such an adjustment of the land surface to the sea-surface as promotes systematic shelf-building and the development of shelf-seas as set forth in Article II of this series. We have found that ordinary diastrophic movements are, in the main, inimical to the close adjustments required. Continental creep is, however, regarded as essentially independent of ordinary orogenetic or epeirogenetic diastrophism; indeed it is regarded as, in a sense, their reversal. Its action is suspended or overwhelmed by movements in the opposite direction when a diastrophic revolution is in progress. It is only when ordinary diastrophism is quiescent and the continents are in their relatively static stages that the slow, gentle reactionary movement of creep is presumed to be appreciable.

Now this is not so much a vertical movement as a horizontal one, though actuated by gravity. It is indeed downward in a degree but it is horizontal in its main expression. By reason of this, it is fitted to become a copartner with gradation in leveling the land and thus facilitating an advance of the sea. It is in itself a massive form of gradation; it works toward a base-level of its

[1] For a discussion of creep in relation to faulting, see T. C. Chamberlin, "The Fault Problem," *Economic Geology*, II, No. 8 (1907), 709–21.

own. While I think its molecular methods are distinctly different from those of a true plastic body, the result is a continental spreading out and flattening down whose aspect is almost identical with that of a plastic body. A block of asphaltum will spread and flatten for years but it finally reaches a state beyond which the movement will not go. It reaches a base-level of a certain sort. So the continents, under the action of glacier-like creep, however great its efficiency may be supposed to be, will merely flatten out to a certain extent and the resulting surface will ideally be of the nature of a sloping plain closely analogous to the peneplain produced by erosive degradation.

So far as creep may be supposed to affect the continental shelf it moves it outward and slightly downward, and this fits the shelf surface for the reception of more sediments. If the downward component of the movement were greatly in excess of the rate of sedimentation, it would carry the shelf out of good working adjustment, much as in the case of ordinary diastrophism, but it seems highly improbable that the creep movement depresses the surface of the continental shelf faster than sedimentation naturally builds it up, even when the general continental creep is supplemented by the special creep in the soft sediments of which the younger upper and outer portions of the shelf are formed. The work of creep in thus pushing the shelf outward and slightly downward relieves wave-action of a part of its burden in building out the shelf and so enhances the joint effect. It seems safe therefore to regard creep as a co-operating adjunct to both parts of the gradational work, the leveling of the lands and the building-out of the shelves.

The outward creep of the continents reduces the capacity of the ocean basins and thus aids in lifting the sea-level and forcing the waters to creep out upon the lowered land. In this way also it co-operates with erosive gradation, which by transferring a portion of the land to the sea in another way raises the sea-level and causes its advance on the land.

While the great sea-transgressions—and the great terranes of parallel strata to which they gave rise—imply a relative freedom from diastrophism while forming, the details of bedding and

faunal distribution give evidence of minor oscillations, of advances and retreats of the sea, of shiftings of outlines, and of changes of barriers and connections, the effect of which is to introduce special features in the sedimentation and local or regional variations in the faunas. These features were subordinate to the grander deployments both in area and in time, and in this subordination they suggest that they may have been due to minor and perhaps separate agencies that acted more continuously and in smaller units —more easily and variously shifted—than the profound deformative agencies that were liable to interrupt the whole process. Gentler agencies whose general activities were harmonious with the main sedimentary process seem better fitted for this function than a supposed feeble action of a titanic agency whose normal action would put an end to the whole process.

There is an aspect of continental creep, if we may follow the analogy of glaciers, that seems to fit it for this function. The suggestion is at least worth entertaining and testing as a working hypothesis. The creeping body of a glacier does not always decline steadily in the direction of its motion but rather assumes a more or less undulatory mode of progress. While the advancing surface, taken as a whole, slopes forward, it may, in a subordinate measure, slope backward, i.e., *rise* in the direction of its advance. On broad glaciers of nearly flat surfaces, there are sometimes swells and sags; the surface water sometimes gathers into lakelets, and occasionally streamlets of notable size flow in a direction *opposite* to the flow of the glacier beneath.[1] These anomalies are assignable to irregularities in the rock floor over which the ice mass is thrust by its internal stresses. The creep of a continental embossment, if it follows the glacial analogy, may be assigned a similar undulatory mode of progress. If continental creep is facilitated by a shear zone that had been formed previously by the powerful stresses that actuated the lateral crust movements of earlier times, the shear planes of the zone are not probably perfectly plane; they are much more probably undulatory, for the surface effects of the diastro-

[1] See T. C. Chamberlin, "Glacial Studies in Greenland," *Jour. Geol.*, II (1894), 784, Fig. 12, view of a portion of Blase Dale Glacier showing the undulation of its surface involving a backward inclination. For a backward flowing stream see Vol. V (1897), 231–32.

phism and probably the basal effects were undulatory. The glacier-like rock mass in being thrust by its own internal stresses over these undulatory shear planes—in effect an undulatory floor like that of the glacier—must probably have gently swelled and sagged as does ice under similar conditions. The sea, or any other water-body, lying upon this creeping undulating sheet would suffer shiftings of outline, changes of deposition, rises and removals of barriers, attended by variations of faunal development. While these might rise to some moment, and might seem to be epeirogenic in nature, they would not usually suspend the main progress of sea-transgression, but rather, on the whole, be tributary to it, whatever their temporary or local effect might be. If this source of minor oscillations shall ultimately find warrant, it will relieve us of referring these various slight intercurrent undulations of the surface to those deep-seated potent agencies whose normal action is refractory rather than compliant with the gradational agencies on whose well-adjusted action the development of the great stratigraphic terranes, as a whole, are dependent.

THE GENERAL PRINCIPLES UNDERLYING METAMORPHIC PROCESSES

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PART II

THE PHASE RULE

The phase rule, which recently has been applied to metamorphic rocks,[1] orients us as to the number of phases which, for a given number of components and for given external conditions, can be in equilibrium with one another. According to the phase rule $f=c-n+2$, where f, c, and n are the number of degrees of freedom, of components, and of phases, respectively.[2] If f is zero, the system is stable only when temperature, pressure, and concentration (composition) of each phase have definite and singular values. If f is 1, a change of one of the above three parameters induces definite and definitely related alterations of the other two, if the number and nature of the phases is to remain unaltered. If f is 2, any two of the above parameters may be changed; such a system can exist at any pressure or temperature within certain limits, although under such circumstances the composition of all the phases present is at

[1] V. M. Goldschmidt, *Kontaktmetamorphose im Kristiania-Gebiet*, Kristiania, 1911, and in other papers; P. Niggli, "Chloritoidschiefer des nordöstlichen Gotthardmassives," *Beiträge geol. Karte Schweiz*, N. F., XXXVI (1912).

[2] "A heterogeneous system is made up of different portions, each in itself homogeneous, but marked off in space and separated from the other portions by bounding surfaces; these homogeneous, physically distinct, and mechanically separable portions are called *phases*" (Findlay, *Phase Rule*, p. 9).

"As the *components* of a system there are to be chosen the *smallest number* of independently variable constituents by means of which the composition of each phase participating in the state of equilibrium can be expressed in the form of a chemical equation" (*ibid.*, p. 12).

"The number of degrees of freedom of a system is the number of the variable factors, temperature, pressure, and concentration of the components, which must be arbitrarily fixed in order that the condition of the system may be perfectly defined" (*ibid.*, p. 15).

For a full discussion of these matters the reader is referred to Findlay's book.

any moment definitely fixed. Thus a system with two degrees of freedom can in general exist throughout a range of temperatures and pressures; if the system actually had only one degree of freedom, it could only be accidental if the corresponding values were chosen. Therefore the number of possible phases coexisting *in equilibrium* during metamorphic processes will in general not be greater than the number of components. The essentials of the phase rule and their application to simple systems are so readily understood that there is always a temptation to neglect their specific limitations; limitations which are especially prominent when, as in the case of metamorphic processes, we endeavor to reason backward from the end-result of the process.

Limitations to the applicability of the phase rule to metamorphic systems.—Application of the phase rule presupposes that the pressure (and temperature) is uniform throughout the system[1]. Now it is clear that absolutely uniform pressure (or temperature) can never occur during rock metamorphism; we may have anything from great inequality in the stresses in the three principal directions to a nearly equal distribution of the three stresses. On the relative and absolute magnitude of the variation of the resultant stress from point to point depends its influence on the result. If the particular paragenetic transformation can still go on in spite of considerable variations of either temperature or pressure from the mean values which actually obtain, it will not be much affected by the local stress variation; if otherwise, great local variation of results may be expected. Moreover, similarly variable results will be produced by the changes of temperature and pressure which accompany the process of metamorphism.

Reference to the discussion of phases and components given in the textbooks renders it evident that great caution must be exercised in guessing (inferring) the actual components from an examination of the more or less ultimate state of any given rock. It is an essential property of a component that it is always in reaction with the other members of the system throughout the establishment of equilibrium. But the fact that under laboratory conditions

[1] Further, that there are (*inter alia*) no surface effects; this condition might be unfulfilled in certain cases, e.g., with very porous rock-masses.

a component is so insoluble that its rate of reaction seems so small as to be negligible does not prove that in geological phenomena, for which unlimited time is available, the influence of such a component can be neglected. Moreover, the similarity in chemical nature of certain oxides does not justify grouping them together as a single component, in an effort to simplify the system under consideration; for the behavior of the numerous two-component systems hitherto studied shows that the grouping-together of the oxides of the alkalies, or of the alkaline earths, or of alumina and iron, is of doubtful validity.

By means of the microscope it is often possible to distinguish between original and new components. The presence of any original components which could not have been formed by the metamorphic process indicates that the forces were not intense enough, or did not last long enough, to render the alteration complete; we have then an incompletely metamorphosed rock. On the other hand, the presence of original quartz grains alongside new quartz (as is frequently observed) is no proof of incomplete metamorphism, because quartz, which is stable throughout a very wide range of conditions, may appear in spite of considerable variation of chemical composition, temperature, or pressure. Again, it is a question of the stability of the new forms. When one recalls how frequently metastable forms appear in laboratory work and considers the special circumstances of metamorphism, one need not be surprised if metastable substances occur frequently in nature also even though the conditions of formation remain undisturbed for long periods of time. Metastable forms are observed oftenest with polymorphic or hydrated substances; their occurrence therefore in general changes only the nature, but not the number of the phases present. For instance, so far as the phase rule is concerned, it does not matter though kyanite appear instead of the stable sillimanite.[1]

Metamorphic processes are merely the result of a tendency toward a new equilibrium position; whether this new position of equilibrium is reached or not, depends, however, on a number of factors. It is a question if a rock as a whole can always be con-

[1] The *simultaneous* occurrence of both sillimanite and kyanite would of course increase the number of phases by one.

sidered as a single system, within which complete mutual actions and reactions are possible. This may well be so if the original rock was fairly homogeneous and not too coarse grained. In the case of rocks the solubility of most of the substances concerned is so small that contact with a small amount of material can suffice for the production of saturated solutions; and so the new material will be the same throughout such a system, although the amount of material in solution at any moment is small. But whether all of the original components, which by reason of the changed conditions have become unstable, disappear or not depends upon the rate of reaction, upon the time, and upon the presence of catalytic agencies; furthermore, if any of the components or intermediate or reaction-products are present as grains of appreciable size, they may become coated with some stable substance and hence—owing to the slowness (and even absence) of diffusion in the solid state—be protected against further action.

When to these circumstances which hinder the attainment of equilibrium we add the complications introduced by phenomena such as resorption,[1] the occurrence of reactions in the solid state (including monotropic and enantiotropic changes) and the existence of compounds which, while unstable on fusion, are able to form at lower temperatures; further, when we consider that some of the essential components may by reason of their volatility have escaped from the system and that the influence of pressure upon stability relations is practically unknown—when we remember this formidable array of possibilities, we should hardly expect to draw immediate or final conclusions merely through application of the phase rule in such complicated polycomponent systems as rocks.

Consequently, the phase rule cannot always be expected to hold rigidly or to serve in any manner as an "open sesame" in such studies. What we observe is that there appear, for a given metamorphic process and for a given number of components, only a limited number out of all the possible compounds; moreover, that the number of definite and important minerals formed by a metamorphic process usually does not exceed the maximum number

[1] For an example, see p. 593.

postulated by the phase rule. On the other hand, while in several cases the number of phases found does not exceed the number predicted from a consideration of the phase rule, on the specific assumptions that equilibrium has been reached and that the components have been correctly inferred, yet the presence of more or fewer phases than expected proves nothing except that the assumptions were wrong.

From the discussion of these limitations to the phase rule we conclude, therefore, that our present knowledge of the facts concerned is so scanty that the phase rule is not yet of much service in aiding us to describe the natural history of metamorphic rocks.[1] Nevertheless it may be of assistance in the classification of rocks; for this reason, and in order to emphasize by means of actual illustrations some of the statements made in the above paragraphs, we include a brief discussion of the application of the phase rule to ternary systems.

The ternary system—lime-alumina-silica.—The relative simplicity of two-component systems tempts one to assume that systems of three or more components may somehow be considered in an equally simple manner. That such is not the case is amply demonstrated by the lime-alumina-silica series, which has recently been very thoroughly investigated[2] at constant pressure.

From this work, in which the variables considered are only concentration and temperature, it follows that there are—instead of the simple ternary relation with a single ternary eutectic, such as the textbooks commonly treat—about eighteen invariant points (at which 3 solid phases coexist with 1 liquid phase) any one of which might under proper conditions show the usual eutectic properties (e.g., eutectic structure).[3]

[1] The phase rule will of course be an indispensable adjunct when the experimental facts are available.

[2] E. S. Shepherd and G. A. Rankin, "Preliminary Report on the Ternary System $CaO-Al_2O_3-SiO_2$," *Jour. Ind. Eng. Chem.*, III (1911), 211; *Z. anorg. Chem.*, LXXI (1911), 19.

[3] In passing it may be suggested that the so-called eutectic structure as inferred from the study of alloys may or may not occur in the case of silicates. It is readily conceivable that systems in no sense eutectic may easily yield the so-called eutectic structure and vice versa; cf. Shepherd and Rankin, *loc. cit.*

The provisional diagram given by Shepherd and Rankin is reproduced in Fig. 1; we shall make no attempt to discuss it here, except in regard to two points, viz., (1) the occurrence of resorption, and (2) the formation of very different end-products from systems of very similar original composition.

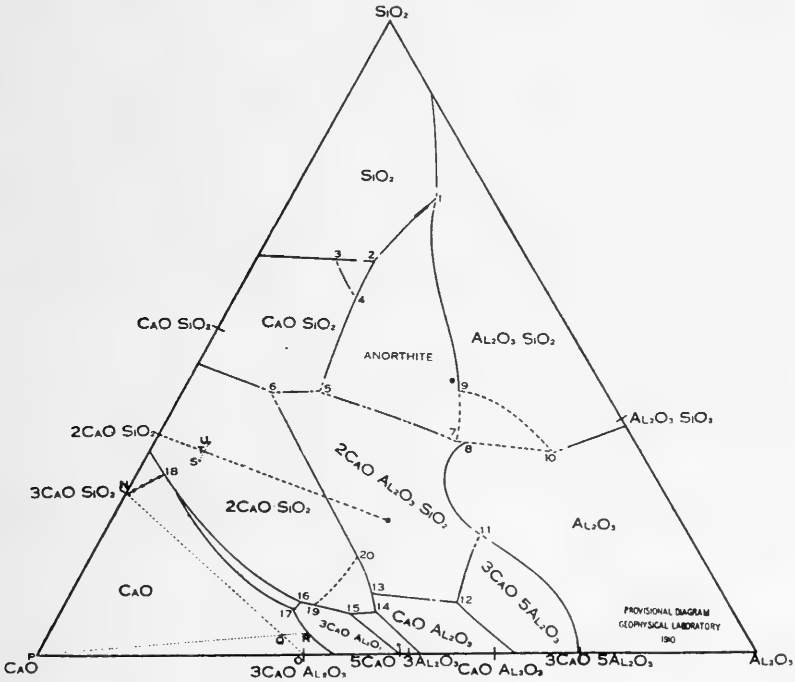

FIG. 1.—Provisional Diagram[1] for System $CaO \cdot Al_2O_3 \cdot SiO_2$

Consider a mixture the composition of which is represented by a point on the line *PQ*, and suppose it to be cooling. Lime crystals separate, the composition of the melt moves along the line *PQR* until the point *R* on the boundary curve *R*–17 is reached. At this point the solid phase ($3CaO \cdot Al_2O_3$) begins to separate, which is possible only by resorption of CaO; the composition of the melt

[1] The position of several of the points which were still doubtful at the time this diagram was published has now been more definitely established by further investigation, the results of which will appear in a forthcoming paper by Rankin. These changes, however, do not affect any of the deductions which appear in the paper of Shepherd and Rankin (*loc. cit.*).

moves along the boundary curve *R*–17 until the invariant point 17 is reached, when the whole solidifies to the three phases (CaO), ($3CaO \cdot Al_2O_3$), and ($3CaO \cdot SiO_2$). In this case only part of the free CaO is resorbed; but if the original composition had been represented by a point on the line *QR* (i.e., outside the triangle *NOP*) the CaO would be completely resorbed, the final crystallization occurring at invariant point 15, at which the phases ($3CaO \cdot Al_2O_3$), ($5CaO \cdot 3Al_2O_3$), and ($2CaO \cdot SiO_2$) are in equilibrium. All of these phenomena occur, be it noted, without interruption of the normal cooling or the intervention of any external disturbing factor.

As regards the second point, consider compositions along the line *STU*, the total length of which corresponds to a change of only 3 per cent in the amount of CaO present. Compositions on the line *ST* solidify at invariant point 16, 15, or 14, according to the original position on the line; the ternary grouping formed is either ($3CaO \cdot SiO_2$), ($2CaO \cdot SiO_2$), ($3CaO \cdot Al_2O_3$), or ($5CaO \cdot 3Al_2O_3$), ($3CaO \cdot Al_2O_3$), ($2CaO \cdot SiO_2$), or ($5CaO \cdot 3Al_2O_3$), ($2CaO \cdot SiO_2$), ($CaO \cdot Al_2O_3$). Compositions on the line *TU* solidify at point 6, forming the grouping ($2CaO \cdot SiO_2$), ($CaO \cdot SiO_2$), ($2CaO \cdot Al_2O_3 \cdot SiO_2$); while the compositions corresponding to *T* (or any point on the line joining the compositions $2CaO \cdot SiO_2$, $2CaO \cdot Al_2O_3 \cdot SiO_2$) behave as binary systems, solidifying to the two phases ($2CaO \cdot SiO_2$), ($2CaO \cdot Al_2O_3 \cdot SiO_2$).

These facts—and indeed the general appearance of the diagram—illustrate the complications likely to be encountered in relatively simple systems, and show that for systems of from four to eight or more components appearances afford a plain warning against hasty generalization, even if initial homogeneity of material and the continuous attainment of equilibrium could be assumed.

The ternary system $CaCl_2$-$MgCl_2$-H_2O.—This system, which was very carefully investigated by Van't Hoff, Kendrick, and Dawson,[1] is an example of a system with a variable phase (solution). The determination of the quintuple point of such a system will always be a matter of great difficulty, since in this case pressure, temperature and concentration (composition of the variable phase) are all fixed.

[1] *Z. physik. Chem.*, XXXIX (1902), 27.

At 1 atm. and 21°95 there is equilibrium between the four phases ($MgCl_2 \cdot 6H_2O$), ($CaCl_2 \cdot 6H_2O$), ($CaCl_2$, $2MgCl_2$, $12H_2O$),[1] and solution, the composition of which is $100H_2O$, $4.92MgCl_2$, $9.27CaCl_2$. The reaction may therefore be written as follows:

$$\underset{\substack{\text{Solid}\\ A}}{1\,(MgCl_2 \cdot 6H_2O)} + 1.188\,\underset{\substack{\text{Solid}\\ C}}{(CaCl_2 \cdot 6H_2O)} = 0.252\,\underset{\substack{\text{Solid}\\ B}}{(CaCl_2 \cdot 2MgCl_2 \cdot 12H_2O)} +$$

$$0.101\,\underset{\substack{\text{Solution}\\ L}}{(100H_2O,\ 4.92MgCl_2,\ 9.27CaCl_2)}$$

Now if the temperature is changed, the pressure remaining constant, one of the above 4 phases must disappear; and it has been found that the right-hand side is favored by increase of temperature. Therefore at temperatures below 21°95 and 1 atm. there can coexist: either

$$(MgCl_2 \cdot 6H_2O),\ (CaCl_2 \cdot 6H_2O),\ \text{solution} \qquad (\text{I})$$

or

$$(MgCl_2 \cdot 6H_2O),\ (CaCl_2 \cdot 6H_2O),\ (CaCl_2 \cdot 2MgCl_2 \cdot 12H_2O) \qquad (\text{II})$$

while at higher temperatures the possible stable configurations are either

$$(CaCl_2 \cdot 2MgCl_2 \cdot 12H_2O),\ \text{solution},\ (CaCl_2 \cdot 6H_2O) \qquad (\text{III})$$

or

$$(CaCl_2 \cdot 2MgCl_2 \cdot 12H_2O),\ \text{solution},\ (MgCl_2 \cdot 6H_2O) \qquad (\text{IV})$$

The solution has a definite composition corresponding to each temperature. For instance, at 16°7 in contact with ($MgCl_2 \cdot 6H_2O$) and ($CaCl_2 . 6H_2O$) its composition is $100H_2O$, $6.69CaCl_2$, $5.94 MgCl_2$; while at 28°2, in contact with ($CaCl_2 \cdot 2MgCl_2 \cdot 12H_2O$) and ($MgCl_2 \cdot 6H_2O$), it is $100H_2O$, $8.84CaCl_2$, $5.37MgCl_2$.

From this it is evident that not all the systems whose composition can be expressed in terms of $MgCl_2 \cdot 6H_2O$, $CaCl_2 \cdot 6H_2O$ and H_2O can give the 3-phase combinations I, II below 21°95, or III, IV at temperatures above 21°95. This may be illustrated by the isotherm for 23° (and 1 atm.), which has the general form given in Fig. 2. *PQ* is the solubility curve of *A*, *QR* that of *B* (tachhydrite), and *RS* that of *C*. The point *Q* gives the composition of the solution in equilibrium at 23° with *A* and *B*; *R*, of that in equilibrium

[1] The so-called tachhydrite.

with B and C. The combination (A B, solution Q) can result only when the gross composition is within the triangle ABQ; the combination (B C, solution R), only when the composition falls within BCR. The triangles APQ, BQR, and CRS are the regions in which the two-phase combinations of solutions with A, B, or C, respectively, are stable.

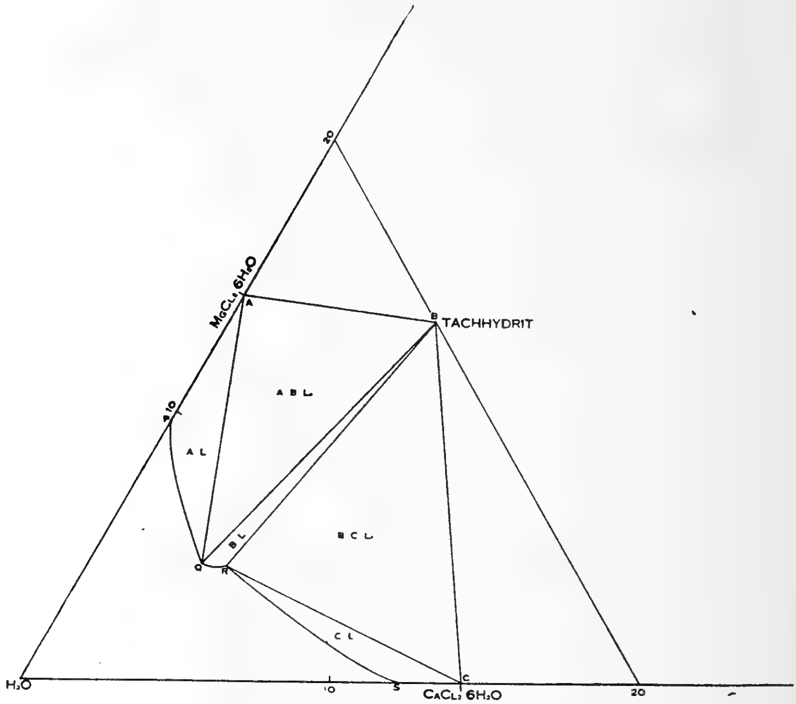

Fig. 2.—Portion of diagram for the ternary system H_2O—$MgCl_2$–$CaCl_2$, representing schematically the solubility isotherms at 23° under a pressure of 1 atm.

If, starting from the equilibrium $ACBL$ at 21°.95, we raise the temperature by 0°.2, we must raise the pressure by 11.8 atm. in order to prevent the disappearance of any of the four phases; this relation was experimentally determined, so that the direction of this particular 4-phase line at 22° is known. Investigation of the combination BCL at higher temperatures (at 1 atm.) showed that at 25° a second 4-phase line is met; at this temperature,

therefore, we have in equilibrium *BCDL*, where *D* stands for the solid phase ($CaCl_2 \cdot 4H_2O$). Thus the reaction ($CaCl_2 \cdot 2MgCl_2 \cdot 12H_2O$) + ($CaCl_2 \cdot 6H_2O$) = ($CaCl_2 \cdot 4H_2O$) + solution now takes place, and instead of III (*BCL*) we then have the combinations *DLC* or *DLB*. For instance, at 28°2 ($CaCl_2 \cdot 4H_2O$) and ($CaCl_2 \cdot 6H_2O$) are in equilibrium with solution of the composition $100H_2O$, 14.4 $CaCl_2$, 1.37$MgCl_2$. The relation between *P* and *T* for the 4-phase equilibrium *CDBL* is not known; but by analogy we may consider that its general course is similar to that of the curve for *ACBL*.

All of these relations are exhibited in the subjoined figure (Fig. 3), which represents a part of the ideal figure. From it we see again how relatively small temperature changes and large pressure changes alter the type of the 3-phase, and also of the 2-phase, combinations.

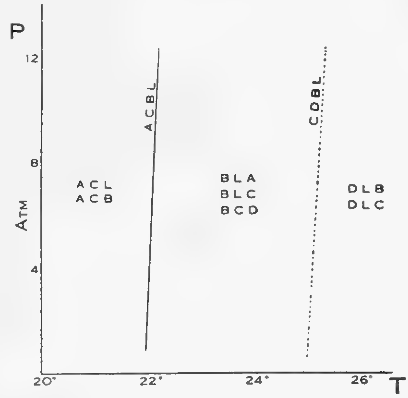

FIG. 3.—Portion of *PT* projection for system $H_2O \cdot MgCl_2 \cdot CaCl_2$, representing the stable 3-phase groupings and two 4-phase lines.

Consideration of an ideal case.—Let us suppose that between the four minerals *ABCD*, whose compositions may be expressed in terms of the three components *K*, *L*, and *M*, the relation $n_1A + n_2B \leftrightarrows n_3C + n_4D$ exists;[1] it being assumed further that there are no false equilibria or unstable combinations. At arbitrary pressure and temperature only three of these can coexist; let the right-hand side be favored by lowering of temperature and of pressure. Then at low temperatures and small pressure, we should have the stable combinations *ABC* or *ABD;* at high temperatures and pressures, *CDA* or *CDB*.

[1] This equation is analogous to the equation already given for the system $CaCl_2 \cdot MgCl_2 \cdot H_2O$. The complete analytical presentation of the relations for ternary systems is given by Schreinemakers in *Heterogene Gleichgewichte*, III, 210 f., which the reader desirous of fuller information with regard to ideal cases is advised to consult. (This book forms the third volume of the treatise, of which Vols. I and II only were completed by Roozeboom.)

Let us assume further that the minerals X, Y, Z are stable both above and below this inversion point, that they are made up of other components and do not affect the equilibrium relations of $ABCD$. We could then have the rocks $XYZABC$ (I), $XYZABD$ (II) on the one hand, $XYZCDA$ (III), $XYZCDB$ (IV) on the other. These four types are the ideal ones in the temperature, pressure and concentration region characterized by the relation $n_1A+n_2B \leftrightarrows n_3C+n_4D$. Now if a rock of type I comes into the temperature and pressure regions of types II or III, then D must be formed and either A or B must disappear.

Now the relations in actual metamorphic processes are complicated by a number of factors: that the rate of reaction is often small, that metastable forms occur, or that false or partial equilibrium only is attained. Hence we cannot know if a relation observed in the study of thin sections of a series of rocks is really characteristic of the temperature and pressure conditions which obtained during the process of metamorphism. Nevertheless, although the whole transformation may be metastable, it may be profitable to consider the ideal relation involved.

On the other hand, the formation of a variety of combinations is favored by the circumstance that pressure and temperature change during the metamorphic process and that the co-ordinates of the invariant point of neighboring and chemically very similar rocks may be different. Indeed in geologic units one seldom finds the production by metamorphism of a single type of mineral composition; instead of this there is usually a whole series, the individual members of which are closely interrelated. To take a few examples which have been investigated, there are: the hornblende porphyroblastic schists of Tremola[1] (Gotthard, Switzerland); the glaucophane schists of Syra[2] (Greece) and of the Val de Bagne[3] (Wallis, Switzerland); the chloritoid schists of the Garvera[4] region (Gotthard); the eclogites of the Ötztal[5] (Tyrol), etc.

[1] L. Hezner, *Neues Jahrbuch f. Min.*, Beilage Band XXVIII (1908), 157.

[2] H. S. Washington, *Am. Jour. Sci.* (4), XI (1901), 35.

[3] T. Woyno, *Neues Jahrbuch f. Min.*, Beilage Band XXXIII (1911), 136.

[4] P. Niggli, *Beiträge geol. Karte Schweiz*, N.F., XXXVI (1912).

[5] L. Hezner, *Tsch. Min. Petr. Mitteil*, XXII (1903), 437, 505.

In concluding this section we wish to state again our precise standpoint with reference to the application of the phase rule. To say that the phase rule must always hold for metamorphic systems is equivalent to the assumption that such systems always attained a state of equilibrium; which is certainly not true. Many rocks will be found to contain a larger number of minerals than the maximum number required by the phase rule. On the other hand, the fact that the number of minerals found agrees with this maximum is absolutely no criterion of the attainment of a state of stable equilibrium within the system; for at equilibrium there will in many cases be present fewer phases than this maximum number. One may say only that the rocks will show a tendency toward equilibrium, that they will tend to attain the state corresponding to the ideal *PT* diagram; the ideal types therefore are to be considered merely as representative examples which also will be of use in classifying actual rocks.

Consideration of ideal types may also be of great advantage in classifying metamorphic rocks; just as in the classification of crystals the ideal crystal form is used, although it is seldom that two crystals of the same substance separate out in precisely identical form. As an instance of its use in this way we may recall the well-known work of V. M. Goldschmidt on the contact rocks of the Christiania region.

The foregoing treatment applies only to cases where the metamorphic process has not been accompanied by any change in the gross composition of the material; the question of what happens in such case is taken up later. Here we will remark only that it is by no means necessary that rocks which *now* show identical chemical compositions should be made up of the same mineral constituents; for the reason that differences, and comparatively slight differences, in the amounts of volatile components ("mineralizers") *originally* present might easily alter the character, and order of separation, of the minerals formed in the metamorphic process.

THE GENERAL EFFECTS OF NON-UNIFORM COMPRESSION

The effects produced by exposure to non-uniform compression are in general permanent; that is, the original state of the system

is not re-established when the compression ceases. The effect of differential compression may be resolved into two parts: that due to a (smaller) uniform pressure and that due to a shearing stress, the latter being the preponderating effect. The mere fact that "flow" or deformation of the compressed material occurred is sufficient evidence that unequal stresses were set up; in other terms, that the compression was not uniform. In discussing this question it will be convenient to treat first the effects of stress on a solid phase alone before passing on to the consideration of systems solid-liquid or of those in which we may imagine the appearance of a liquid phase to be one of the results of stressing the solid phase; the latter is much more fundamentally important in relation to metamorphic processes than the former.

The effects of stress on the solid phase alone.—The effects of stress on solids are what we are accustomed to call mechanical; they are subsidiary, rather than essential, in metamorphic processes. For this reason, and because the general subject has been discussed by Willard Gibbs, while its geological applications form the subject of a number of well-known papers,[1] the effects of stress on solids will be treated very briefly here.

Any directed stress acting on a particle may be resolved into three stresses, each acting on an element of surface in one of the three principal planes. These three stresses are represented both in direction and intensity by the three principal axes of an ellipsoid. The stress produces in the particle a strain, which will tend to change the shape of the particle, or its size, or both together. At any point there will be three mutually perpendicular directions in which the displacement is a maximum or minimum and about which these displacements will be symmetrically arranged as an ellipsoid is about its three axes. A homogeneous isotropic sphere exposed to the action of a stress will assume the form of the so-called strain-

[1] C. R. Van Hise, "Metamorphism of Rock and Rock Flowage," *Bull. Geol. Soc. Am.*, IX (1898), 269; G. F. Becker, "Finite Homogeneous Strain Flow and Rupture of Rocks," *Bull. Geol. Soc. Am.*, IV (1893), 13; "Schistosity and Slaty Cleavage," *Jour. Geol.*, IV (1896), 429; "Experiments on Schistosity and Slaty Cleavage," *Bull. U.S. Geol. Survey 241* (1904); C. K. Leith, "Rock Cleavage," *Bull. U.S. Geol. Survey 239* (1903); L. M. Hoskin in *16th Annual Report, U.S.G.S.*, Part I, 1896; P. Niggli, *Beiträge geol. Karte der Schweiz*, N.F., XXXVI (1912).

ellipsoid, the position of which, and thus the state of strain, at any point is completely determined.

The strain- and stress-ellipsoids are parallel to one another only in isotropic media, and then only when the stress acts continuously in a definite direction. The presence of particles of unequal hardness —in other words, heterogeneity of the material—results obviously in the cessation of this parallelism. The position of the strain-ellipsoid is influenced by the exact distribution of the particles of unequal hardness; and, on the other hand, the position of these fine layers—in so far as it can change at all—is determined by the direction of the strain-ellipsoid (tectonic displacements). The orientation of newly formed mineral grains is determined in general by the relations of stress and strain, the most thorough adaptation being attained when flow cleavage takes place. In the crystalline schists formed under stress which show heteroblastic structure the orientation of the porphyroblasts is indefinite, which is presumably due to their rate of formation. That their orientation does not correspond to the conditions of strain is evident from the fact that subsequent rotational movements have sometimes occurred,[1] accompanied by cataclastic phenomena. Cataclastic effects predominate in the so-called mylonitized rocks, which are found principally where thrusting has taken place.

The optical properties of crystals are influenced by stress. Isotropic minerals may become biaxial, if the direction of the principal stress does not correspond with that of the axes of symmetry. Uniaxial crystals become optically biaxial when the direction of the stress is other than that of the optic axis of the crystal; for instance, in crystalline schists quartz occurs frequently as optically biaxial crystals, which at the same time show elliptical, in place of circular, polarization, and undulatory instead of definite extinction. Application of stress changes in general the position of the principal axes of biaxial crystals; when the stress-ellipsoid is parallel to the ellipsoid derived from the crystalline axes there will be a change only in the refractive indices and in the optic axial angle.

Furthermore, stress may to some extent produce gliding or translational displacements in the individual mineral grains. As

[1] P. Niggli, *Beiträge geol. Karte Schweiz*, XXXVI (1912), 61.

instances of the phenomena of gliding, calcite frequently is found twinned in the $(10\bar{1}2)$ plane; diallage also frequently exhibits lamellae which have resulted from stress. Translational displacements are those in which the displaced portion remains parallel to its original position; this phenomenon is shown—though usually only to a small extent—by plastic crystals, such as cyanite, augite, mica, graphite, calcite, brucite, when they occur in metamorphic rocks.[1]

On the other hand, many crystals found in crystalline schists are the net result of a more or less thoroughgoing destruction of the original configuration of the system and of more or less shattering of the individual crystals, followed by a healing-up of the cracks and spaces thus produced. To account for this we are led to consider the effect of stress on the processes of fusion and solution.

Effects of stress on systems solid-liquid.—It has been shown in two previous papers[2] (to which the reader desirous of a fuller discussion of this topic is referred) that the observed effects of non-uniform compression can be satisfactorily correlated by ascribing them to the action of "unequal" pressure, that is, to a pressure which, in a system solid-liquid, acts on the solid phase but not, or not to the same extent, on the liquid phase. It can readily be shown from thermodynamic reasoning that the effect of unequal pressure is *always* to lower the melting point (or raise the vapor pressure, and hence the solubility) of a substance, and by an amount which is many times as great as the effect (raising or lowering) produced by the same pressure acting on both phases simultaneously.

The principle that unequal pressure lowers the melting-point was formulated first in 1881 by Poynting,[3] who applied it only to calculate the effect on the melting-point of ice. In 1892 the result was stated by Le Chatelier,[4] who applied it to several problems of

[1] See papers by O. Mügge, e.g., *Neues Jahrbuch f. Min.*, I (1898), 71; II (1899), 55; also L. Milch, *ibid.*, I (1909), 60.

[2] J. Johnston, *Jour. Am. Chem. Soc.*, XXXIV (1912), 788; *Z. anorg. Chem.*, LXXVI (1912), 361; J. Johnston and L. H. Adams, *Am. Jour. Sci.*, XXXV (1913), 205; *Z. anorg. Chem.*, LXXX (1913), 281.

[3] *Phil. Mag.* (5), XII (1881), 32.

[4] *Z. physik Chem.*, IX (1892), 335.

geological interest—to the regelation of ice and the consolidation of beds of gypsum.

In a paper[1] first published in 1894, E. Riecke discussed the effect of a one-sided pressure (a stress) on the melting-point of ice, and quite recently he has restated his conclusions in a second paper.[2] Riecke's formula for the lowering of melting-point of ice effected by the stress Z (tensile or compressive) is

$$\Delta T_1 = -\alpha Z^2$$

where (for ice) α has the value 0.00036 when Z is expressed in kg. per sq. cm.[3] He appears to consider this formula, which was developed for the case of a single crystal only, valid only for small values of Z; so that its range of applicability is somewhat limited. It has, under the name of the Riecke principle, been adduced occasionally by geologists[4] to aid in correlating observations connected with metamorphic processes and results.

The basic principle underlying Riecke's reasoning is identical with that used in the derivation of the equation used in the present paper, which, as mentioned above, was derived first by Poynting; but the latter, which is derived from general thermodynamic principles without specific assumptions (other than those common to all thermodynamic reasoning), is much more generally applicable, holding as it does for solid aggregates, and for any range of pressures, subject always of course to the condition that the pressure acts on the solid phase, but not, or to a less extent, on the liquid phase produced by melting or by solution.

Derivation of the formula: The derivation of the formula by means of which the effect of unequal pressure on a substance is computed is based on the thermodynamical fact that unequal pressure acting on any phase increases the "activity" of that phase, or its tendency to pass over into another phase; in other terms, unequal pressure acting only on the solid phase increases its vapor pressure and its solubility (in any particular solvent) and lowers

[1] *Nachr. Ges. Wiss. Göttingen*, 1894, 278; *Ann. Physik*, LIV (1895), 731.

[2] *Centralblatt Min. Geol.*, 1912, p. 97.

[3] 1 atmosphere = 1.033 kg. per sq. cm.

[4] For instance by Grubenmann, *Die kristallinen Schiefer*, 2 Aufl. (1910), and by Becke, *Denkschriften Wien Akad.*, 7 Mai, 1903.

its melting-point. Into the steps in the derivation of this formula it is unnecessary to enter here;[1] the final differential equation is:

$$\frac{dT}{dP}=\frac{TV_s}{\Delta H} \tag{V}$$

which expresses the lowering of melting-point by unequal pressure in terms of the absolute melting-point (T) and the molecular volume (V_s) of the solid at the temperature and pressure in question and ΔH, the molar heat of fusion under those conditions. The quantities V_s and T are always positive, but ΔH (as here used) is always negative; hence application of excess pressure on the solid phase *always* lowers the melting-point.

If we compare the melting-point depressions (dT_1 and dT_2 respectively) produced by the same excess pressure (dP) acting on (1) the solid phase alone, (2) both phases; that is, if we combine equations V and I, we obtain the result

$$\frac{dT_1}{dT_2}=\frac{V_s}{dV}=\frac{V_s}{V_s-V_l} \tag{VI}$$

or, expressed in words, the ratio of the lowering of melting-point of the solid phase, when this alone is subject to a given pressure, to the alteration (raising or lowering) observed with the same (given) pressure acting uniformly on both phases is equal to the ratio of the (specific) volume of the solid phase to the change of (specific) volume on freezing.

This equation shows how many times greater the melting-point lowering is when the pressure acts only on the solid phase. For example, the melting-point of ice is lowered by unequal pressure 12 times as much (or 0°09 per atm.) as by uniform pressure (0°0075 per atm.); in general $\Delta T_1/\Delta T_2$ is much greater than 12, because the fractional change of volume accompanying melting is usually much smaller than it is in the exceptional case of ice.

The (unequal) pressure (ϕ, expressed in atmospheres) required to cause a substance to melt at the temperature T_2 can be computed if we can integrate equation V. We cannot perform this integration rigidly for lack of the necessary data on the variation of

[1] It is discussed in another paper: see *Jour. Am. Chem. Soc.*, XXXIV (1912), 788-802; *Z. anorg. Chem.*, LXXVI (1912), 361-79.

ΔH and V_s with pressure and temperature; but fortunately the variation of $V_s/\Delta H$ is small and for the present purpose unimportant. We may therefore consider $V_s/\Delta H$ to be independent of pressure and temperature; by integration and transformation we then obtain the equation

$$\phi = 95.1\ QD \log \frac{T_1}{T_2} \qquad \text{(VII)}$$

which gives the unequal melting-pressure (ϕ) at the temperature T_2 in terms of the heat of melting (Q, in calories per gram), the density D, and the ordinary melting-point at 1 atm. pressure (T_1, in absolute measure). At the present time the data requisite for the

TABLE III

LOWERING OF MELTING-POINT OF METALS EFFECTED BY ONE ATM. UNEQUAL PRESSURE; TOGETHER WITH THE COMPUTED MELTING-PRESSURES (IN ATM.) AT ORDINARY TEMPERATURES

METAL	MELTING-POINT		HEAT OF FUSION Q	DENSITY D	ΔT_1	ϕ_{27}
	t	T_1				
K	62	335	15.7	0.87	0.59	64
Na	97	370	31.7	0.98	.29	266
Pb	327	600	5.4	11.37	.24	1,760
Sn	232	505	14.1	7.29	.12	2,200
Bi	270	543	12.5	9.80	.11	3,000
Cd	321	594	13.7	8.64	.12	3,300
Al	658	931	42.0	2.60	.21	5,100
Zn	419	692	28.0	7.1	.084	6,900
Ag	960	1,233	23.0	10.50	.12	14,000
Cu	1,083	1,356	43.0	8.93	.086	24,000
Pd	1,550	1,823	36.3	11.4	.11	31,000
Pt	1,755	2,028	27.2	21.5	0.084	46,000

calculation of ϕ are available only for a few metals; these calculations have been made and the results are presented in Table III; the sixth column (headed ΔT_1) gives the melting-point depression[1] produced by 1 atm. excess pressure acting on the solid, the last (headed ϕ_{27}) contains the computed pressure (in atmospheres) which, acting on the solid alone, would be required to cause the substance to melt at 27°.

[1] As calculated by the formula $\Delta T_1 = \dfrac{T_1}{41.30\ QD}$, which is easily derived from equation V.

By comparison of the above results with those of Table I we see how much greater the effect of unequal pressure may be. For example, take the case of lead, the melting-point of which is changed $+0^\circ.008$ by 1 atm. uniform pressure, but $-0^\circ.24$, or 30 times as much, by 1 atm. excess pressure on the solid phase.

The sequence of the metals when arranged in the order of their ϕ values (as computed from equation VII) is identical with that obtained when they are arranged in the order of their flow pressures or of any of their elastic properties (e.g., tensile strength, hardness). This parallelism is a striking corroboration of the effectiveness of unequal pressure in correlating phenomena attending the deformation of crystalline solids.[1]

It is of interest to inquire if there is any relation between the hardness of minerals and any of their other properties. There is a parallelism between the hardness of the metals (as ordinarily measured) and the calculated ϕ values, which depend upon the density, heat of melting, and temperature of melting. Of these three factors the first lies within comparatively narrow limits for a series of minerals; the second is not known, but probably lies also between comparatively narrow limits *in general*;[2] the limits within which the melting-point lies are comparatively much wider apart. Consequently, we should expect that there is a rough parallelism between the hardness of minerals and their melting-point.

That this expectation is justified is shown by Fig. 4, in which the melting-point of those minerals which give congruent melting-points is plotted against the hardness; this has been done for all minerals for which the necessary data could be found in Landolt-Börnstein *Tabellen*. All of the points lie within a zone the breadth of which is no greater than one might expect from the very uncertain nature of the measurements of hardness, and in view of the circumstance that the latent heat has not been taken into account. When the latent heat is taken into account (which is possible only for a few of the metals) and the ϕ values plotted against hardness the

[1] For a discussion of this question see Johnston, *Jour. Am. Chem. Soc.*, XXXIV (1912), 788; *Z. anorg. Chem.*, LXXVI (1912), 361.

[2] The exceptional cases would be those in which the heat of melting is very small.

points lie within a very much narrower zone. From this we can infer that the same will be found for the minerals when the requisite data are known.

There is therefore a considerable body of evidence then which suggests that any permanent deformation of a crystalline dry aggregate is determined by an actual melting of some part of the material—a melting which occurs as soon as the local stress reaches the melting-pressure corresponding to the temperature of the material—with subsequent resolidification; this resolidification consists in the production of crystals of that form which appears

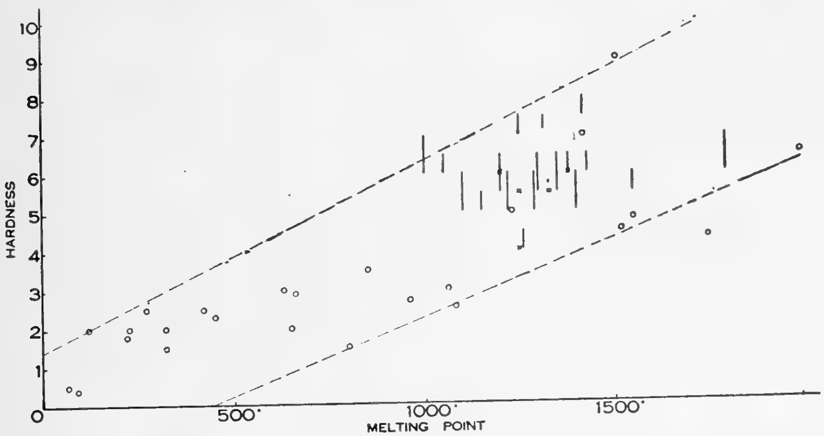

FIG. 4.—Diagram to exhibit the relation between hardness (as ordinarily measured) and melting-point. Circles represent elements; crosses or lines represent minerals, lines being used where the tables give a value such as 5.5—6.5.

most readily under the particular conditions of pressure (and therefore not necessarily of the original form) and, so far as the argument is concerned, recrystallization need not be complete. So far as we are aware, there is no evidence which directly contradicts the above hypothesis; on the contrary this hypothesis enables us to correlate and interpret a large number of diverse and apparently contradictory observations.[1]

This type of compression accounts easily for regelation; the most common example is the regelation of the substance water which, as it happens, is exceptional in that its freezing-point is

[1] See Johnston and Adams, *Am. Jour. Sci.*, XXXV (1913), 205.

lowered by uniform pressure. This phenomenon cannot in general be produced by uniform pressure because uniform pressure raises the melting-point of most substances; so that we shall with advantage consider unequal pressure to be the effective factor in the case of water as in that of other substances. Consider a block of ice at o° supporting a loaded wire. The pressure exerted by the wire depresses the melting-point of the ice by an amount Δt; immediately beneath the wire, therefore, we have at any instant a thin layer of ice at $-\Delta t$ in equilibrium with water at $-\Delta t$. The water, however, escapes round the wire, and so comes into contact with ice at o°; such a system is, however, unstable, for under these conditions water cannot remain subcooled. Consequently, the water freezes again and forms a solid block above the wire.

The process by which a mass of loose snow is compacted into a block of ice is identical with this. The pressure, due to the superincumbent material, lowers the melting-point at the surface of contact of adjacent grains; the water at $-\Delta t$ flows into the interstices where the pressure is smaller and freezes again. This process continues until the interstices are all filled up, that is, until a solid block of ice is formed. This again, we believe, is the general mode in which consolidation of a mass of originally loose material takes place, as for instance in the welding of metals and in pyrometamorphic processes. The consolidation of loose mineral material, however, takes place more usually through a process of solution, the general principle being identical in both cases; this we shall now consider.

Influence of unequal pressure upon the solubility of solid substances.—Considerations in every respect analogous to the foregoing are applicable to systems of a solid in contact with water or other solvent; in such cases, pressure acting in excess on the solid increases its solubility,[1] and thus renders the solutions supersaturated with respect to the *unstressed* solid. Le Chatelier[2] accounts in this way for the consolidation of natural beds of rock-salt, gypsum, calcium carbonate, and clay. To test this matter directly he

[1] The amount of this increase of solubility can be computed from equations analogous to those applicable to melting-points.

[2] *Z. physik. Chem.*, IX (1892), 335.

compressed sodium chloride or sodium nitrate in contact with its saturated solution to about 200 atmospheres for a period of eight days, and found that blocks resembling rock-salt and marble were formed in this way. Similarly one can account for the formation of rigid sandstones from beds of originally loose sand.

Application to metamorphic processes.—The processes just discussed have a very important bearing on rock metamorphism wherever stress has been an important factor. The unequal pressure increases the activity of the solid components, and fusion or solution occurs wherever the local stress reaches the appropriate value. In this way larger amounts of material come into local solution to be immediately redeposited (at points where the stress is smaller) in the form characteristic of those particular conditions, and hence not necessarily in the original form; consequently reactions occur more readily in stressed rocks. The nature and form of the new crystals depend therefore upon the relations of stress and strain in the mass. The so-called Riecke principle has been adduced in this connection; but the whole question has been handled in a much more general way by Willard Gibbs,[1] from whom we quote the following sentences:

> If a solid which is homogeneous in nature and in state of strain is bounded by six surfaces perpendicular to the principal axes of stress, the mechanical conditions of equilibrium for these surfaces may be satisfied by the contact of fluids having the proper pressures, which will in general be different for the different pairs of opposite sides, and may be denoted by p', p'', p'''. It will then be necessary for equilibrium with respect to the tendency of the solid to dissolve that the potential for the substance of the solid in the fluids shall have certain values μ', μ'', μ''', which are entirely determined by the nature and state of the solid.

From Gibbs' equations it follows directly that μ' is "greater than the value of the potential which would be necessary if the solid were subjected to the uniform pressure p'" (and similarly with μ'', p'', μ''', p''').

That is, the fluids in equilibrium with the solid are all supersaturated with respect to the substance of the solid, except when the solid is in a state of hydrostatic stress [uniform pressure]; so that if there were present in any one of

[1] "Equilibrium of Heterogeneous Substances," *Collected Papers*, pp. 196–97. The question was first treated by James Thomson, *Trans. Roy. Soc. Edinburgh*, XVI, 575; *Proc. Roy. Soc.*, XI, 473; *Phil. Mag.* (4), XXIV, 395.

these fluids any small fragment of the same kind subject to the hydrostatic pressure of the fluid, such a fragment would tend to increase. Even when no such fragment is present. . . . . the presence of the solid which is subject to the distorting stresses will doubtless facilitate the commencement of a solid of hydrostatic stress upon its surface. . . . . But in the case of a solid of continuous crystalline structure, subjected to distorting stresses and in contact with solutions satisfying the conditions deduced above . . . . within certain limits the relations given must admit of realization, especially when the solutions are such as can be easily supersaturated.[1]

In other words, when a crystal is strained, the solubility on the strained face is increased. Consequently material tends to dissolve off the strained faces of a crystal in contact with a saturated solution in any solvent, and to be redeposited where the strain is less.[2] The effect of this is that the crystal changes in such a way as to diminish the stress upon it—an example of the well-known principle that the readjustment of a system following disturbance of equilibrium is always such as to minimize the effect of the disturbing factor.

In order to illustrate how stress affects crystallization let us suppose an isotropic sphere exposed to stress. The stress may be resolved into three stresses acting along axes mutually perpendicular; the sphere is thereby deformed into an ellipsoid, the axes of which in the simplest case coincide with those of the stress-ellipsoid. The final effect is the same when the substance is immersed in a solvent medium, for the solubility is increased most in a plane perpendicular to the greatest stress.

Let us consider now the growth under stress of new isotropic particles. The stress would tend to make the particle ellipsoidal, even though it were to make equal growth in all directions. But the saturation limit is reached soonest in the plane perpendicular to the smallest stress, so that the isotropic particle in growing assumes of itself the form of the strain-ellipsoid. From this it follows that particles growing in a stressed medium will be flattened in a direction perpendicular to the greatest stress and will be paral-

[1] W. Gibbs, *loc. cit.*

[2] This does not necessarily imply that the material be redeposited on the unstrained faces of the original crystals; it may go to form new individuals. In very many cases, of course, a reaction or transformation will occur, so that the material will not be redeposited in its original form.

lel to one another; their arrangement thus corresponds exactly to flow cleavage.

The anisotropic character of minerals (also with respect to their solubility relations) introduces a complication, without, however, affecting the general principle involved. A definite arrangement of minerals with respect to a single vectorial property is often found; such an arrangement can of course only be ascribed to the vectorial properties themselves, whether they be differences in solubility or in cohesion.

In metamorphic rocks exhibiting flow cleavage the flakes of mica lie in such a way that the smallest growth was perpendicular to the base, the greatest growth in the basal (and cleavage) plane. We must remember that the immediate influence of stress and strain is made evident in an unequal development in different directions, although the general principle alone gives us no information as to the particular vectorial direction which is parallel to the smallest development. But when we take into account the anisotropy exhibited by the original tiny particles, we must include as one of the factors the orientation of the original particles with respect to certain directions within the crystal; those directions, namely, parallel to the plane (gliding plane) in which displacement of the crystal particles is most readily effected, and perpendicular to the plane (cleavage plane) in which the crystal most readily splits. When the rates of growth or the solubility relations are anisotropic, specific effects analogous to the above will be produced; but of this influence little that is definite can at present be said except that it certainly is appreciable.

From this it follows that the relicts will tend to assume the form of the strain-ellipsoid (if we neglect for the moment the complications introduced by anisotropy). And indeed it is well known that the quartz relicts in rocks originally conglomerate are more or less oval in form. Further, the recrystallization will tend to take place in such a way that the strain is a minimum. This is the basic principle underlying the phenomenon of flow cleavage; for it corresponds to minimum expenditure of work in producing the new formation, or in other words it represents the most complete adaptation of the system to the strains acting upon it.[1] The

[1] P. Niggli, *Beiträge geol. Karte Schweiz*, N.F., XXXVI (1912), 46.

flow of rocks has been studied experimentally, notably by F. D. Adams and his collaborators;[1] it resulted always in the production of a kind of cleavage.

It is characteristic of those cases of metamorphism where stress has been the predominant factor that the system, taken as a whole, is not in simple equilibrium, but rather in a stationary condition only. Now since, as we have seen, unequal stress acts mainly by depressing the melting-point and by raising the solubility, it follows that its effect on the transformation solid-solid is very small. Consequently we might expect that the forms produced under unequal stress would often be forms which cannot be obtained from ordinary melts; and this indeed is often observed.

Let us compare the mineral composition of the crystalline schists (which have very often been formed under stress) with that of eruptive rocks or with metamorphic rocks of the Katazone, making use of the summary given by Grubenmann[2] (see p. 613).

From this summary it is evident that many of the minerals occurring in rocks which have been subjected to unequal stress occur also as ordinary products of the secular alteration of magmatic minerals at low temperatures. The water content of many of them determines in large part their behavior when heated or melted under ordinary conditions. Nevertheless the paragenesis of the stress minerals is, as Grubenmann has pointed out, characteristic of relatively low temperatures. Stress has increased the "activity," so that in stressed systems some reactions readily take place which otherwise would go very slowly. Thus unequal stress may be regarded as a kind of catalytic agent, though in thinking of it in this way one must remember that it has frequently a characteristic influence on the nature of the products of a reaction, in addition to its influence on the rate of formation of those products.

In spite of the fact that in stressed systems we are not dealing with simple equilibrium conditions, we may apply principles similar to those set forth on p. 597 to ideal typical systems. In doing

[1] *Phil. Trans. Roy. Soc. London*, A, CXCV, 363; *Am. Jour. Sci.*, XXIX (1910), 465; *Jour. Geol.*, XVIII (1910), 489; *XI Congrès geol. internationale*, II (1910), 911.

[2] *Die kristallinen Schiefer*, 2. Aufl., 1910.

this we would consider only a simple equilibrium characteristic of relatively low temperatures, remembering always that the conclusions reached by this means are subject to considerable limitation; still such conclusions may be useful for purposes of classification, if for no others.

Main Components	Stress Mineral	Corresponding Minerals in Katamorphic Rocks or in Eruptive Rocks	Products Obtained on Heating or Fusing the Stress Mineral
H_2O, Al_2O_3, K_2O, SiO_2......	Sericite	Alkali feldspar, muscovite?	Leucite, nephelitic mineral, glass
H_2O, Al_2O_3, K_2O, MgO, FeO, SiO_2..................	Biotite	Biotite	Olivine, spinel, leucite(?), glass
H_2O, MgO, FeO, SiO_2.....	Chlorite	Partly biotite, partly olivine, spinel, augite	Spinel, olivine +?
H_2O, FeO, SiO_2, Al_2O_3......	Chloritoid	Cordierite+sillimanite, spinel	....
H_2O, FeO, Al_2O_3, SiO_2.....	Staurolite	Same as chloritoid	....
H_2O, Fe_2O_3, Al_2O_3, CaO, SiO_2	Epidote	Consist of plagioclases in combination with pyroxenes, etc. Epidote is also a primary constituent of some granites	Anorthite and lime-augite
H_2O, Al_2O_3, CaO, SiO_2.....	Zoisite	Consist of plagioclase	....
H_2O, CaO, MgO, SiO_2......	Nephrite, actinolite	Augite and olivine	....
H_2O, MgO, FeO, CaO, Al_2O_3 alkalies, SiO_2...........	Hornblendes	(In part) basaltic hornblendes or pyroxenes	Pyroxene+ olivine
Na_2O, Al_2O_3, SiO_2 $\begin{Bmatrix} FeO \\ MgO \end{Bmatrix}$...	Glaucophane	?	?
CaO, MgO, FeO, Al_2O_3, SiO_2	Garnet	Garnet, plagioclase, olivine, pyroxene	Anorthite, monticellite, melilite, olivine, meionite
Al_2O_3, SiO_2...............	Kyanite (Andalusite)	Sillimanite, andalusite	....

Influence of stress on reactions accompanied by the production of a vapor phase.—In considering the effects of stress it is absolutely essential to note that the influence of stress on reactions which are accompanied by the evolution of a gas or vapor is enormous. For instance, it is well established that continued grinding in a

mortar of minerals containing water or even of substances containing water of crystallization results in a loss of water;[1] thus apophyllite on grinding lost about 1 per cent of water (Thugutt), $MgSO_4 7H_2O$ lost about 2.5 per cent H_2O (Blecker). Moreover, Johnston has found[2] that some carbon dioxide can be driven off from a substance as stable as calcium carbonate by grinding it in a mortar for a few minutes; in this case the grinding lowers the temperature at which the calcium carbonate exhibits an appreciable pressure of carbon dioxide by some 500°.

This behavior is in thorough accordance with the standpoint adopted with regard to the effects of unequal pressure. Application of precisely similar reasoning leads to a formula entirely analogous to equation V, namely:

$$\frac{dT_p}{dP} = \frac{T_p V}{\Delta H} \qquad \text{(V}a\text{)}$$

where T_p is the temperature corresponding to a given pressure of the vapor phase, ΔH the heat of reaction, and V a (specific) volume, which practically will be intermediate between that of the original solid and the volume change accompanying the reaction. Furthermore, we see that the unequal pressure required to produce an appreciable pressure (p) of the vapor phase at a given temperature would be approximately proportional to $Q \log T_p$,[3] T_p being the temperature at which the system in the unstressed condition would exhibit the vapor pressure p, and Q the heat of dissociation; and this conclusion is roughly borne out by the observations hitherto recorded.

Analogous considerations apply to reactions such as $RCO_3 + SiO_2 \rightarrow RSiO_3 + CO_2$; the general conclusion being that unequal stress will cause reactions between solids accompanied by the devel-

[1] Mauzelius, *Sveriges Geol. Undersökning Arsbok*, I (1907), No. 3; W. F. Hillebrand, "Influence of Fine Grinding on the Water and Ferrous Iron Content of Minerals and Rocks," *Jour. Am. Chem. Soc.*, XXX (1908), 1120: *Chem. News*, XCVIII (1908), 205, 215, who refers to some earlier observations; S. J. Thugutt, *Centr. Min. Geol.* (1909), p. 677; I. B. Blecker, *Chem. News*, CI (1910), 30.

[2] A separate note dealing with this question is in course of preparation.

[3] Since from one substance to another there is comparatively little variation of V, but large variations of Q and T_p.

opment of a gas phase to proceed to an extent which would be inappreciable in the absence of stress. This renders it evident, as has been noted on a previous page, that great care must be exercised in choosing points for purposes of a geologic thermometer; for the only points really adapted to this purpose are transitions solid-solid (which, moreover, must not be much affected by uniform pressure), while systems in which a vapor phase intervenes are altogether useless for this purpose.

METAMORPHISM ACCOMPANIED BY ADDITION OF MATERIAL

Hitherto we have considered only those cases of metamorphism where there was no addition of material during the process; this limitation permits us to consider the changes produced in a given chemical system by a change in its physical conditions and environment. As a matter of fact, chemical investigation of metamorphic rocks[1] has shown that in many cases the gross composition of the original eruptive or sedimentary rocks has remained sensibly unaltered by the metamorphic processes;[2] in other cases, on the other hand, it has shown that an addition of material did occur during the process of metamorphism.

Now the addition of material, whether temporary or more or less continuous during the process, is often the main cause of the changed physical conditions, therefore the cause of the metamorphic process. When this is so the chances for a complete transformation of the rock are in general more favorable than when temperature and pressure alone are variables. Thus it is that in rocks which have been metamorphosed with, or by, the addition of foreign material there are peculiarities in mineral content and often in texture and structure. In all such cases it is to be noted that the gross composition of the rock *now* can give us no certain idea of the composition of the system during metamorphism, and therefore that two rocks which now have the same bulk composition may then have represented quite different chemical types.

[1] Grubenmann, *Die kristallinen Schiefer*, II. Teil, 2. Aufl., 1910.

[2] The occurrence of small changes of composition, such as have been noted, e.g., by J. D. Trueman (*Jour. Geol.*, XX, 228 f.), is an occasional, but certainly not a general, phenomenon. Such small changes exert no marked specific influence on the general result, and consequently are not specially discussed here.

The term metamorphism with addition of material we reserve for the changes characterized by a penetration of the original rock by some foreign system; we do not use it to denote the small local changes in concentration which may have taken place. The foreign system, the viscosity of which must be comparatively small, will generally be of magmatic origin; we must therefore briefly consider magmatic processes.

Magmas are mixed solutions of silicates, charged with volatile substances, the so-called gas mineralizers, the amount of which, varying with the progress of the intrusion and solidification, depends upon the previous history and original composition of the particular magma basin. Of these volatile components, the majority can exist, *when alone*, only as gases at the temperature at which the magma crystallizes.

Analysis of volcanic exhalations has led to the recognition of the following gases and vapors, excluding those of minor importance: H_2O, H_2, N_2, CO_2, CO, H_2S, SO_2, HCl, Cl_2, CH_4, HF, SiF_4. Which of these appear under given conditions depends mainly upon temperature and pressure, the latter especially, since it influences the equilibrium greatly when the reaction is accompanied by a change in the total number of molecules (especially therefore in cases of dissociation or association). Conversely, reaction will frequently take place in gaseous systems when the pressure changes, therefore in magmatic gases when they escape into a region of lower pressure. Such reactions are often attended by a large evolution of heat, which is doubtless one of the sources of heat, and possibly even one of the causes of volcanic outbreaks. For any reaction which evolves much heat and proceeds very rapidly may be explosive; for instance, hydrogen and oxygen explode when set off by a spark, that is, when the reaction is started at a high temperature (where its rate is very great), the amount of heat evolved by the reaction being sufficient to prevent a lowering of the temperature of the zone reacting at any moment. When one takes into account the reactivity of gases and the dependence of the position of equilibrium at any moment upon the effective temperature and pressure at that time, one is led irresistibly to the view that from the gases found in the exhalations no safe con-

clusion can be drawn as to the nature of the gaseous phase present in the intrusive magma unless the conditions existing there and their influence upon the equilibrium are all known. Nay more, it is to be expected that the exhaled gases do not represent an equilibrium at all, but are actively in the process of reacting.[1]

The magma also contains, in addition to the above gases and vapors, a number of other substances which are volatile at high temperatures, such for example as metallic sulphides, chlorides or fluorides, and compounds containing boron.

It is not at all necessary that the gaseous components, such as H_2O, H_2S, HCl, SO_2, exist as gases in the magma, even when they are present in the free state and not as compounds. For in that case it is their miscibility with the magma—or in other words, their solubility in it under the particular conditions (of which pressure is obviously the most important)—which determines whether they are present in the liquid phase.

The critical temperature, above which a system can exist only as gas, is a function of the chemical composition of the system. A gas when dissolved in a mixture of non-volatile components will exhibit a higher critical temperature than it does in the pure state; such a solution would of course exert in general a considerable gas pressure, which, however, need not be as great as the critical pressure of the volatile component in the pure state.[2] To illustrate: the critical temperature of SO_2 is 157°5, its critical pressure is 79 atm. Now if 24.7 parts $HgBr_2$ (the melting-point of which is 236°5) and 75.3 parts SO_2 are heated in a sealed glass tube, the volume of which is so chosen that the pressure will be about 80 atm. at 157°, melting of the $HgBr_2$ takes place at 230°.[3] This lowering of 6°5, which is due to the taking-up of SO_2 by the

[1] Day and Shepherd, for example (in the course of an investigation as yet unpublished), find that the gases emerging from the volcano Kilauea contain CO, CO_2, S, SO_2, H_2O, H, Cl, and F—a mixture of gases which cannot possibly coexist in equilibrium.

[2] A full discussion of these matters will be found in P. Niggli, *Z. anorg. Chem.*, LXXV, 161; LXXVII (1912), 321; *Central. Min.*, 1912, p. 321; *Geol. Rundschau*, III (1912), 472. The main points, especially in case the volatile component is water, are treated by Morey and Niggli, *Jour. Am. Chem. Soc.*, XXXV (1913), 1086 f.

[3] *Z. anorg. Chem.*, LXXII (1912), 161 f.

melt, shows that at a pressure of about 100 atm. a considerable quantity of SO_2 is condensed or dissolved in a melt of $HgBr_2$ at 230°, in spite of the fact that the critical temperature of pure SO_2 is 157°.5.

In precisely the same way we can have at high pressures water, or any of the other gases, present in the magmatic melt, and at the same time lowering its melting-point considerably below what it would be were no volatile components present.[1] Initially the amount of volatile component might be small, but its proportion in the liquid would increase (if the pressure remained constant, i.e., unless gas can escape) as crystallization progressed, unless the gas itself entered largely into the solid minerals.

On the other hand, gaseous material at high pressures and at temperatures above the critical can exert some degree of solvent action, as is evident from the following reasoning. The volatile component *A* as liquid can dissolve the non-volatile component *B*. Now unless the solubility of *B* in liquid *A* diminishes very rapidly near the critical point, there will be at that point a definite amount of *B* in solution. But since at the critical point the liquid and gaseous phases are by definition identical, there must then be the same proportion of *B* in the gaseous phase; so that above the critical temperature we can have a gaseous, or better a fluid, solution of a non-volatile substance. In general there is a very marked falling-off in solubility just below the critical point, but this in itself is no reason why at still higher temperatures and pressures the solubility of *B* in *A* should not again increase.

For instance, in fluid SO_2 at 159°.4 and at a pressure of about 80 atm. the solubilities of $HgBr_2$ and HgI_2 are respectively about 1.5 per cent and 0.7 per cent by weight. At 230° in the same volume (hence at correspondingly higher pressures) the amount of $HgBr_2$ dissolved is about 8.5 per cent, while at 254° about 6.2 per cent HgI_2 dissolves in the fluid phase. This example illustrates only the possibility of the phenomenon; the quantitative results cannot of course be transferred to magmatic systems. But the two cases are entirely analogous in principle, and the residual phase from solidification of the magma, even though it be gaseous, is to be looked upon as a solution.

[1] Direct evidence bearing on this point will be presented in the near future.

Under magmatic conditions the volatile substances (such as H_2O, SO_2, CO_2, etc., all of which are to be treated in exactly the same way) may in part unite with some of the other constituents to form more or less stable compounds which may be liquid under the conditions of temperature and pressure obtaining. The proportion combined in this way is controlled by temperature and pressure, the effect of the latter being to raise the concentration in the gas phase and hence, in accordance with Henry's law, in the liquid phase also. An idea of the influence of temperature is afforded by the following recently obtained results: in a melt of 1 mol. K_2O and 0.94 mol. SiO_2 heated in an atmosphere of CO_2 at 1 atm. pressure there is at equilibrium at 900,° 0.33 mol. CO_2 present as carbonate, while at 960° and 1000° the corresponding amounts are 0.28 and 0.24 mol.[1]

In the magma, therefore, the proportion of gas and liquid is a function of chemical composition, of temperature, and especially (because of its relation to concentration) of pressure. In the process of crystallization the concentration of that portion of the volatile components which does not crystallize out as compound or as solid solution will increase relatively in the residue. Eventually, therefore, a fluid solution under high pressure will remain, which will escape whenever an opportunity presents itself, as for instance along tectonic lines. When the volatile components can escape slowly but continuously they will obviously not be under very high pressure, and the amount of material carried by them will be small. Consequently in such cases the main effects are due to the change of temperature and the production of a more or less homogeneous medium by impregnation with the volatile components (especially when water is a factor), which results finally in a fairly uniform recrystallization of the original rock.

The extent of metamorphism is governed in large degree by the nature of the original rock; for instance, by its permeability, which is doubtless one of the chief reasons why limestones in contact with eruptive rocks are much more extensively metamorphosed, and contain a greater percentage of pneumatolytic minerals, than the shales. Moreover, its chemical composition may be a factor, if it is such that reaction may take place between any of its com-

[1] P. Niggli, *Z. anorg. Chemie* (in course of publication).

ponents and the penetrating gases (fluorides, sulphides, etc.). Furthermore, the conditions of formation of the original rock are of importance, as indeed they are with any metamorphic process; for if these conditions were not very different from those which obtained at the period of metamorphic action, the amount of this action would be slight, because there would be either no tendency toward another equilibrium or only an instability of single phases.

Usually in cases of contact metamorphism there is a small pneumatolytic addition of material, which may be temporary or permanent. If it consists essentially in a saturation with water vapor it will materially favor recrystallization. In the rock close to an eruptive contact there is often observed an increased concentration of alkalies, especially of soda. In sediments—clays and shales—there is usually more potash than soda, a predominance which is correlated with the relative solubility or stability of potash- and soda-minerals, since clastic sediments are in large measure merely residues, the least soluble portions of the original material under the particular conditions to which it has been subject. Contact-metamorphosed shales and schists, on the other hand, often have a much larger soda-content than the unaltered material of the same horizon, as is illustrated by the following analyses of rocks in the Christiania region, as given by V. M. Goldschmidt.

	Contact Metamorphic	Unchanged Schists from the Same Locality	
		1	2
SiO_2	54.95	54.43	49.46
TiO_2	1.15	.....	0.89
Al_2O_3	16.32	15.93	19.44
Fe_2O_3	2.95	8.42	1.37
FeO	5.66		6.03
MnO	0.16	.....	0.11
MgO	4.89	3.50	4.68
CaO	3.88	3.56	3.16
Na_2O	*5.56*	*0.74*	*1.55*
K_2O	3.56	3.44	4.12
C	.....	0.66	.....
Loss on ignition	0.71	7.19	6.37
FeS_2	.....	.....	0.29
CO_2	.....	.....	3.70
	99.79	97.87	101.17

The same observation has also been made by others, among them L. Hezner[1] in schists of the Gotthard region. In this case the additions did not take place at the period of intrusion, but during the tectonic disturbances, a fact which shows that the phenomenon is not due to a difference of volatility of soda and potash compounds at high temperatures, but to differences of solubility. Corresponding to this, the solutions emanating from eruptive rocks usually contain more soda than potash, a fact which is correlated with the high soda content of sea-water.

The occurrence of relatively small amounts of such substances as hydrofluoric acid, boric acid, hydrofluosilicic acid, which often are present in magmatic solutions and emanations, can be noted in the mineral content, though the general characteristics of the rock are otherwise altered but little. Such additions produce certain minerals characteristic of contact-metamorphic rocks: such as fluorite (F), scapolites (chlorides), axinite, tourmaline (B), ores (S, As, Sb), lime silicates or quartz in metamorphosed carbonates (Si).

If intrusion proceeds relatively rapidly, or if solutions (fluid or liquid) at high pressure remain over from the process of solidification, there will be an intensive penetration of the surrounding rock with magmatic material. The escape of the magmatic solution follows along the lines of least resistance, producing numerous veins and dykes; in originally sedimentary rocks the direction of these is that of the stratification, or in case the rock has been (or is simultaneously) subject to tectonic disturbance, they lie in the direction of the cleavage planes produced thereby. An interfoliation of the rock may therefore be produced in this way.

A further consequence of intense penetration with hot magmatic material is a considerable rise of temperature in the surrounding rock, which produces the characteristic phenomena of thermometamorphism and *Sammelkristallisation* (increase in size of the crystals). In the neighborhood of injected veins the crystals of a mineral are commonly larger than they are at some distance from it. The tendency to growth of crystals exists because small crystals of any substance are unstable with respect to larger crystals.

[1] *Neues Jahrbuch f. Min.*, Beilage Band XXVIII (1908).

Growth actually takes place only when the temperature is high enough for the rate of growth to be appreciable.

The occurrence of this phenomenon in precipitates in contact with water is frequently used to advantage in analytical operations, to coarsen the grain of precipitates and so render them easier to filter. It has also been demonstrated on a system containing no water by Rinne and Boeke,[1] who, by heating up calcite crystals of various sizes in gas-tight bombs to high temperatures (1,000°) for considerable periods, found that the grains had become nearly uniform in size. Of similar import is the well-known fact that a glass may be made to crystallize in a temperature region in which it is by no means fluid, the optimum effect occurring usually at a temperature 20°–50° below its eutectic temperature.

When rock fragments are surrounded by liquid magma, it will act as a solvent and corrode the fragments in a manner depending upon the temperature and chemical composition of both. On the other hand, the solid particles act as crystal nuclei toward the magmatic solution, at least if its temperature is such that crystallization is possible. It is to be noted that rock transformations, due to partial meltings and recrystallizations, may take place at temperatures far below the melting-points of the individual minerals present; for such processes the positions of the various possible eutectic points are the essential criteria. Thus it is well known that mixtures of solid components in eutectic proportions can be liquefied by long-continued heating at the eutectic temperature, which may be very much lower than the melting-point of any one of the components.

The question as to whether solid fragments sink or float in the magma cannot be decided by density measurements made at ordinary temperature, but its answer involves a knowledge of change of volume with temperature, and requires, in addition, that the influence of viscosity and of gas evolution be considered.

R. Brauns has lately directed attention to a new type of metamorphism, the so-called pyrometamorphism, a term which he has used to denote the effects of hot gases in partially melting[2] some

[1] *Tschermak's Petr. Mitt.*, XXVII (1908), 293.

[2] This idea has also been made use of by Daly in his paper on "The Nature of Volcanic Action," *Proc. Am. Acad.*, XLVII (1911), 92–93.

of the ejected blocks found in the Laachersee region. Such corrosion phenomena are also common, for instance, in biotites of injected rocks. This action of hot gases is identical with that of a blast flame, except that some addition of material may at the same time take place.

CONCLUSION

In the foregoing pages we have endeavored to set forth the most important general principles concerned in rock metamorphism—a general term which includes a number of special cases (e.g., contact metamorphism) all of which, however, differ only in the degree of predominance of one (or more) of a definitely limited group of effective factors. These factors are: temperature, uniform pressure, stress (non-uniform pressure), and gross composition of the system at the time of metamorphism; the same, namely, which determine the equilibrium of the relatively simple chemical systems hitherto investigated experimentally. The knowledge gained from a study of these simple systems may be used as a basis for a prediction of the general character and significance of metamorphic processes; though in applying the principles one must always bear in mind those circumstances which oppose the attainment of a state of true equilibrium, such, for example, as slowness of reaction or the formation of metastable intermediate products.

Now, although the general character of the process may be predicted, no particular statement as to the effects produced in a given system by change of any of the above factors can yet be made, owing to lack of the requisite quantitative data. In this connection it is to be noted that the general application of experimental results which obtain for a given system under given external conditions to another system under similar conditions, or even to the same system under widely differing conditions, is subject to considerable limitation. Conclusions drawn from such extrapolation of experimental evidence will commonly be of little value, and may be altogether misleading; moreover, one may as well guess the final result as arbitrarily choose the data required in calculating it. From this we see that the application of the above simple principles, which determine rock metamorphism, to the complicated rock systems will be no simple matter, but will require

extended experimental investigation and a long time. In such investigation the first thing necessary is a definite conception of the general processes of rock metamorphism; this it has been the purpose of the authors to present in the foregoing pages. The choice of particular problems in this large field will doubtless be aided greatly by a study of natural mineral associations from the physical chemical standpoint, a study which at the same time will certainly provide us with information bearing directly on the problems at issue.

WASHINGTON, D.C.
July, 1913

THE PRIMITIVE STRUCTURE OF THE MANDIBLE IN AMPHIBIANS AND REPTILES

S. W. WILLISTON
University of Chicago

There has been much uncertainty and doubt as to the structure of the mandible in the early amphibians and reptiles. The abundant material of paleozoic vertebrates in the University of Chicago museum has enabled me to determine beyond reasonable doubt, not only the intimate structure of the pelycosaurian and cotylosaurian mandibles, but also that of a very typical temnospondylous stegocephalian. A full discussion with figures of the various forms in which I have determined the structure will be published in a more extensive work on Permian vertebrates next June. For the present I give only the more essential, newly discovered characters in the cotylosaurian genus *Labidosaurus* and the stegocephalian *Trimerorhachis*, accompanied by figures of the latter. A brief description of the structure in *Dimetrodon* has already been published by me in *Science.*

The coronoid of *Labidosaurus* extends from about the seventh tooth along the alveolar margin to about one inch back of the teeth, appearing on the inner side of the outer wall of the meckelian orifice as a narrow, thin bone. The bone forms the anterior wall of the orifice, joining the prearticular much as it joins the angular in the alligator. The prearticular covers the inner side of the mandible posteriorly much as in *Trimerorhachis*, though .not so broadly, and extends forward below the coronoid to about opposite the anterior end of the inframeckelian foramen, where it joins the splenial. The splenial, as usual, enters into the symphysis anteriorly and extends back to the inframeckelian orifice about opposite the last tooth, and forms also part of the inferior margin of that foramen; it is only narrowly visible on the outer side of the mandible.

The arrangement of the elements in *Trimerorhachis* will be shown in the figures better than I can describe them. The coronoid (*cor*), in its relations and position, is almost precisely like that of *Labidosaurus*, except that it is broader anteriorly, and does not extend quite as far forward. It bears the small teeth opposite the posterior dental series. The prearticular (*pa*) is a very broad bone, rather loosely united with the adjacent elements in most of the specimens. Its lower margin posteriorly forms the upper margin of the foramen for the chorda tympani. It borders, as usual, the upper inner margin of the posterior meckelian foramen

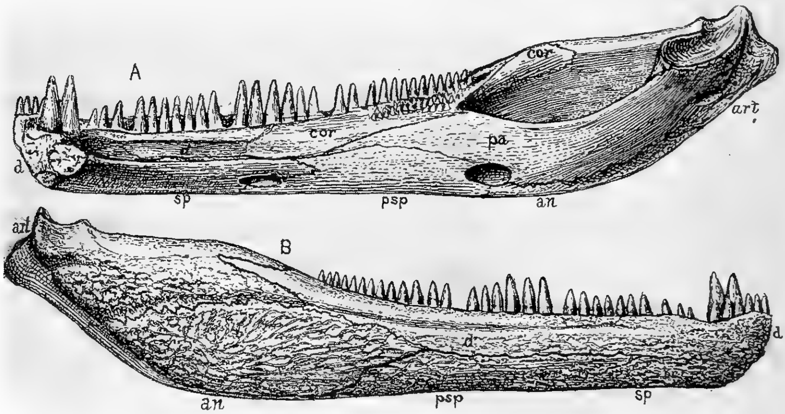

FIG. 1.—Right mandible of *Trimerorhachis alleni* (?) Case, four-ninths natural size: *A*, from within; *B*, from without.

and then continues as a slender projection nearly or quite to the hind end of the splenial. The splenial (*sp*) has precisely the same relations anteriorly as in the cotylosaurs and pelycosaurs, entering more or less into the symphysis and extending back to the anterior margin of the anterior meckelian foramen, and beyond it above to a variable extent. These relations are confirmed in some twenty different mandibles. Lying back of this splenial there is another element corresponding to the posterior part of the splenial in *Labidosaurus*, except that it does not extend beyond the posterior meckelian foramen. It overlaps broadly above the anterior end of the prearticular. I propose to call this bone the

postsplenial, or, if preferred, the *postopercular*. The presence of this element has been definitely confirmed in *Diplocaulus* by Mr. Herman Douthitt, Fellow in Paleontology of the University of Chicago, who will shortly publish figures and descriptions of the cranium and mandible in this genus.

A bone corresponding to that which I call the splenial has been determined in several stegocephalian mandibles; but under a misapprehension of the true relations of the bones posteriorly it has been called the infradentary, after a corresponding element in certain fishes. There can remain no doubt that it is identical with the bone now known to be characteristic of all primitive reptiles, as I have shown, which is certainly the splenial. It is also quite evident that both these bones, the splenial and postsplenial, correspond to the single splenial in the cotylosaurs and the crocodiles. Were we dealing with modern reptiles only, we should be justified in calling the posterior element the true splenial and the anterior one the infradentary. But we cannot conceive of such an anterior development of the posterior bone in *Labidosaurus* and *Dimetrodon* as I have shown to be the case. It is therefore practically certain that it is the posterior bone which has disappeared in the reptiles. Has it fused with the anterior bone? Or has it entirely disappeared? Whatever may be the case, it is quite evident that the bone requires a new name, which I have given it.

I may add that the sutures shown in the figures of *Trimerorhachis* are based upon a prolonged study of more than forty different mandibles of this genus. The sutures separating the articular from the surangular cannot be distinguished in any one of the forty specimens; that between the prearticular and the coronoid is less certain than the others, in its full extent.

FOSSIL FEATHERS AND SOME HERETOFORE UNDESCRIBED FOSSIL BIRDS

R. W. SHUFELDT, M.D.
Washington, D.C.

In addition to the photographs of the slabs of *Archaeopteryx* from the British Museum (*A. lithographica*) and from the Berlin Museum (*A. siemensii*), the material described in the present paper is based upon specimens sent me for the purpose by Mr. Theo. D. A. Cockerell, of the University of Colorado, Boulder, Colo.; by Professor Charles Schuchert, and Mr. C. W. Gilmore. The valuable lot from Professor Schuchert belongs to the Geological Collections of the Peabody Museum of Natural History of Yale University, and those loaned me by Mr. Gilmore belong to the Division of Paleontology of the United States National Museum, in which institution he has charge of the fossil birds and reptiles.

The most important part of this material was photographed by me, and the reproductions of those photographs appear throughout this article. All the figures in the illustrations are reproduced from photographs made by the author direct from the specimens figured.

With respect to the photographs of the two species of *Archaeopteryx*, the one of the British Museum slab was made for me, many years ago, for an illustration to a magazine article I was preparing at the time, and which has long since been published;[1] the other I obtained by copying it from the plate in Vogt's article by means of the camera, it being here reproduced as Fig. 2.[2]

[1] R. W. Shufeldt, "Feathered Forms of Other Days," *Century Magazine* (New York and London, January, 1886), XXXI, No. 3, pp. 352–65. It is Fig. 1 of this article on p. 353 (Fig. 1, below).

[2] Carl Vogt (professor in the University of Geneva), "*Archaeopteryx macrura*, an Intermediate Form between Birds and Reptiles," *The Ibis* (a quarterly journal of ornithology) (London, 1880), IV, 434–56. This is Plate XIII of the article, and is a reproduction of the photograph made direct from the original slab. Professor Vogt's article contains a great mass of valuable information in regard to *Archaeopteryx*, and is, indeed, a veritable classic on the subject, although his views are disputed by some paleontologists, the writer among the number.

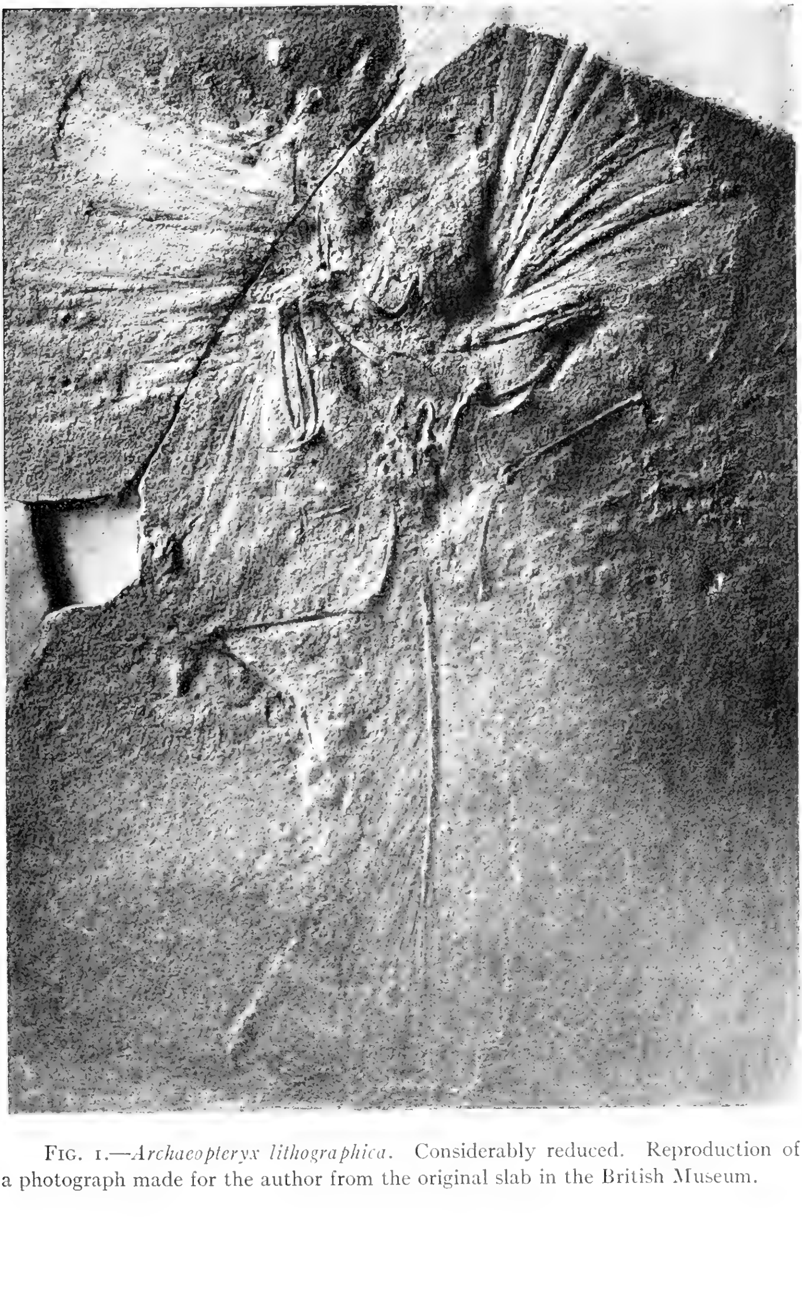

FIG. 1.—*Archaeopteryx lithographica*. Considerably reduced. Reproduction of a photograph made for the author from the original slab in the British Museum.

In this article, and referring to the slab of *Archaeopteryx siemensii* (Berlin slab), Professor Vogt says:

There remain the feathers. Here, no doubt, these are birds' feathers, with a median shaft having barbs perfectly formed. The horny substance of

FIG. 2.—*Archaeopteryx siemensii.* By the author after Carl Vogt. Known as the "Berlin specimen." Considerably reduced.

the feathers has vanished, but the model in the fine paste of the lithographic stone is so perfect that the smallest details may be studied with the lens. The new slab shows all the feathers in their place.

The remiges of the wings are fixed to the ulnar edge of the arm and to the manus; they are covered for nearly half their length with a filiform down. None of them project beyond the others; the wing is rounded in its outline like that of a Fowl [p. 445].

What else Professor Vogt says in this article about the feathers of this famous fossil *bird* from the Upper Jurassic of Solenhofen, Bavaria, is not applicable here, where I desire to discuss only the character of fossil *contour* feathers, as well as "downy" ones.

FIG. 3.—Fossil bird (?) from Florissant, Colo. (1908). Loaned by Theo. D. A. Cockerell, of the University of Colorado. Natural size. Reproduction of a photograph by the author.

Fossil feathers have puzzled paleontologists more than once; and not long ago, Dr. Knowlton, of the National Museum, showed me there, in the collections, some specimens that were originally described as "fossil feathers," but were subsequently pronounced, and proven to be, examples of fossil *ferns* of species since described.

Here in the United States nearly all the specimens we have in museums of the fossil feathers of birds—and they are, comparatively,

of great rarity—have been found in the Florissant formation at Florissant, Colo. Fossil bird feathers, however, have been found in various parts of Europe and elsewhere in the world.

After I had the conversation with Professor Frank H. Knowlton in regard to the mistaking of fossil ferns for birds' feathers, Mr.

FIG. 4.—Specimen shown in Fig. 3, enlarged three and one-half diameters (linear)

Gilmore kindly turned over to me the specimens shown in Figs. 5 and 6 of this article, they being the best of several others the National Museum had like them, and practically all they had. This is a single slab, fortunately cleft, that shows the impress (V) and fossil remains (A) of four primary feathers of a bird's

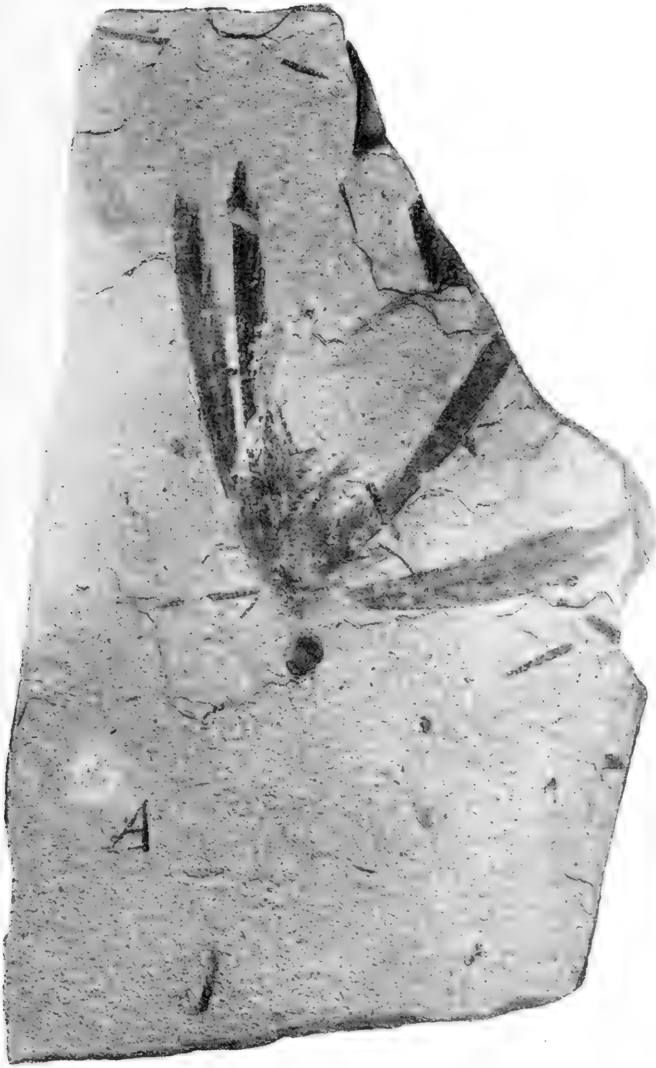

FIG. 5.—Bird feathers. Tertiary: (Oligocene), Florissant Beds, Florissant, Colo. Lacoe Coll. U.S. Nat. Mus. Reproduction of the photograph of the specimen made by the author. Natural size.

wing. They are long and rather narrow, but quite as well preserved, and in precisely the same way as those described for *Archaeopteryx* by Professor Vogt in a previous paragraph. In this specimen, too, there is evidence of some smaller feathers collected about a point from which the primaries diverge. It would appear that maceration had far progressed before these four feathers settled down at the place where they eventually fossilized, and that they had been held together by a single piece of integument at a point common to their attachment to the four apices of the calami. This might likewise have happened had some animal, in devouring this bird, torn off the four feathers, all clinging to a single piece of skin, and that have become separated from the rest of the bird. These feathers belonged to a bird about the same size as, or one perhaps somewhat smaller than, the *Palaeospiza bella* of Allen, and it is quite possible that they may have come from the wing of an individual of that species (cf. Figs. 5 and 6). Both are from the Florissant formation of Colorado.

As it appeared to be eminently desirable that I compare these feathers with those beautifully preserved ones of *Palaeospiza bella*, I made the attempt to borrow the original specimen of that bird, which I was given to understand was the property of the Boston Society of Natural History. In this I was disappointed; and it now appears that that famous slab and invaluable specimen has been *lost* for a number of years. Only recently, both Dr. J. A. Allen—its original describer—and Dr. Glover M. Allen, secretary of the aforesaid society, have written me that, after several most exhaustive searches, not a trace of the specimen can be found, and no clue has been discovered leading to its place of concealment, or in whose possession it was last.

Through the kindness of the librarian of the United States Geological Survey, I was enabled to borrow there a copy of Dr. Allen's description of his *Palaeospiza bella*, and this is now before me.[1] As but few ornithologists in this country and abroad know

[1] J. A. Allen, "Description of a Fossil Passerine Bird from the Insect-bearing Shales of Colorado," *Bull. U.S. Geol. and Geog. Surv.* (F. V. Hayden, U.S. Geol.-in-Charge), IV, No. 2, Washington, May 3, 1878, pp. 443–45; Plate I; Figs. 1 and 2. A most interesting brochure.

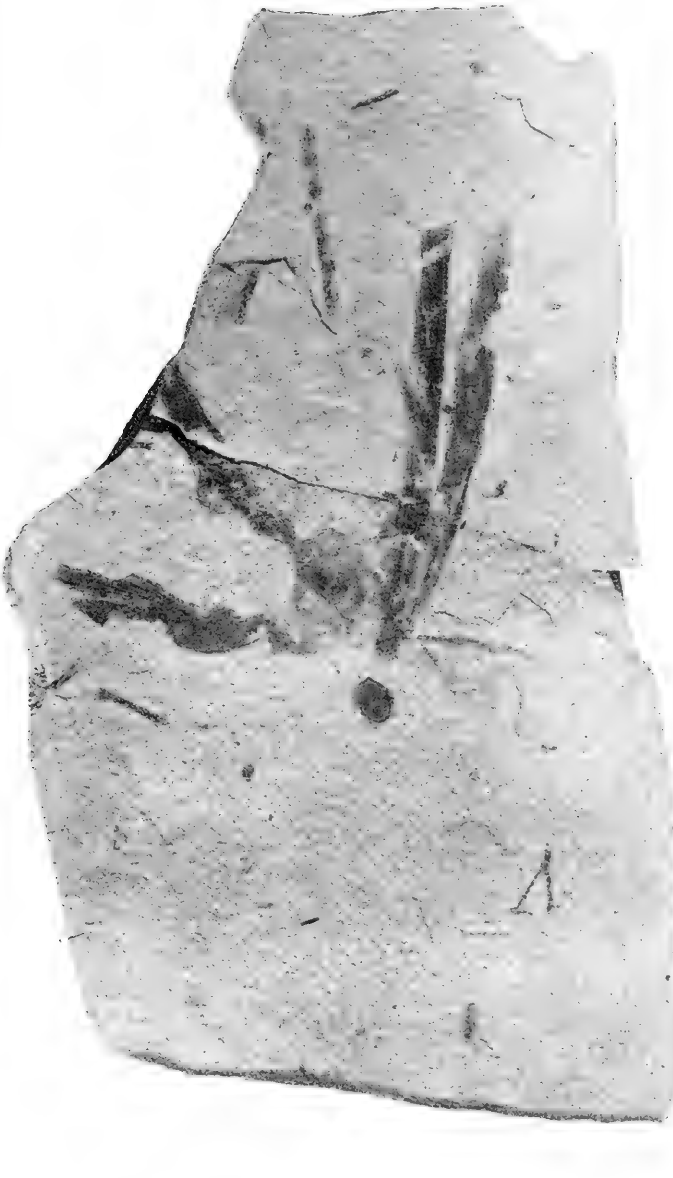

FIG. 6.—Bird feathers. Tertiary: (Oligocene), Florissant Beds, Florissant, Colo. Lacoe Coll. (V), 2 slabs. No. 4225, Coll. U.S. Nat. Mus. Reproduction of the photograph made by the author. Natural size.

of the appearance of this, "the first fossil passerine bird discovered in North America," although, as Dr. Allen remarks, "birds of this group have been known for many years from the Tertiary deposits

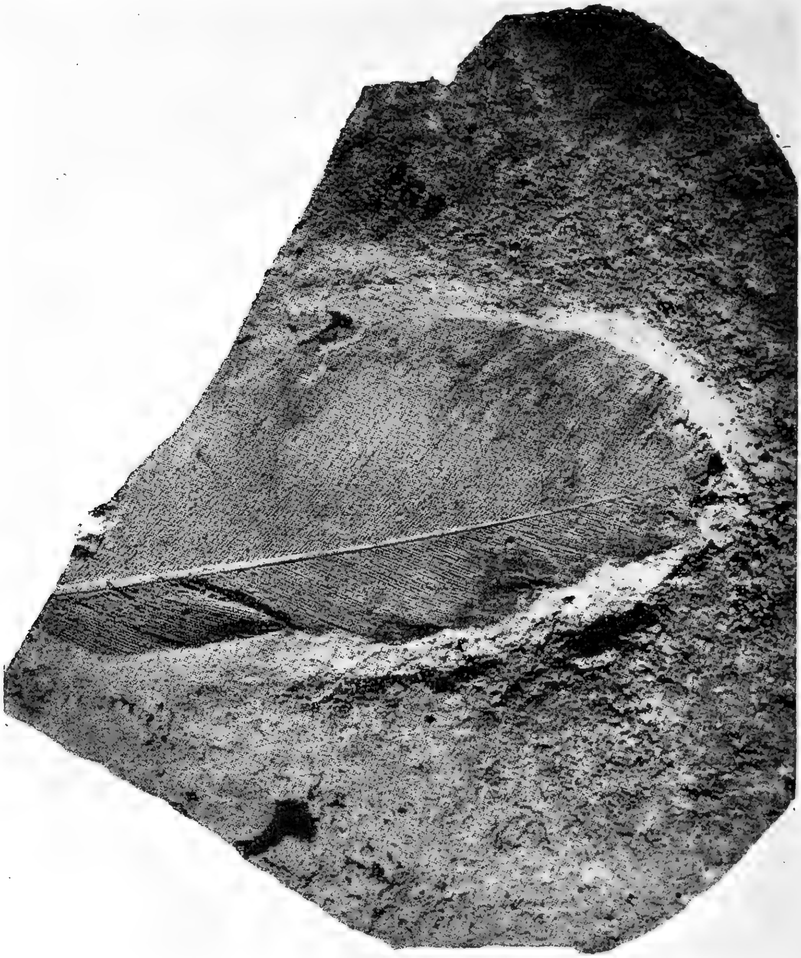

FIG. 7.—Bird's feather. Fresh-water chalk deposits. Gánócz. (Vogelfeder-abdruck in diluvialem Süsswasser-Kalkstein, Gánócz [Kom. Szepes].) Natural size. By the author after Koloman Lambrecht.

of Europe," I must believe that his figures of it, herewith reproduced, will be found to be useful.

Unfortunately, in this specimen everything anterior to the posterior margin of either orbit was not obtained by the collector; so it is quite impossible to state positively that this bird was a "Fringilline" bird. Indeed, Dr. Allen himself states in his paper that "the absence of the bill renders it impossible to assign the species to any particular family" (p. 443). By the aid of my camera I made a somewhat reduced copy of the plate illustrating this contribution, and it is here reproduced as Fig. 8, with the additional figure beside it as in the original.

With respect to the fossil feathers here shown, Dr. Allen further states:

> The specimen bears also remarkably distinct impressions of the wings and tail, indicating not only the general form of these parts, but even the shafts and barbs of the feathers. . . . . The most remarkable feature of the specimen is the definiteness of the feather impressions. Both the shafts and barbs are shown with great distinctness in the rectrices, and the tips of the primaries of one wing are also sharply defined, overlying the edge of the partly expanded tail. The tip of the opposite wing can also be seen beneath the tail.
>
> Another specimen from the same locality, and probably representing the same species, consists of the tip of the tail and about the apical third of a half-expanded wing [here shown in the smaller slab in Fig. 8]. In this example the tail is also pointed and graduated. About seven of the outer primaries of the wing are shown with great distinctness, and two others can be easily made out. The third primary is the longest; the second is slightly shorter; the first and fourth are about equal. There are also in the collection three detached contour feathers of small size, but whether pertaining to the same species as the other specimens cannot, of course, be determined.

From near the same locality, Dr. Allen, in 1871, obtained a few distinct impressions of feathers from the same Florissant shales; but he, in so far as I am aware, never published a specific description of them.

When visiting at my home in the spring of 1913, Mr. Cockerell informed me that it was not a rare event to meet with fossil feathers in those beds similar to the ones here shown in Figs. 5 and 6.

It was Dr. F. V. Hayden, in 1869 I believe, who discovered the first fossil feather of a bird in North America, it having been obtained in the fresh-water Tertiary deposits of Green River, Wyo.—a locality where so many fossils have been collected. Marsh described this specimen as "the distal portion of a large

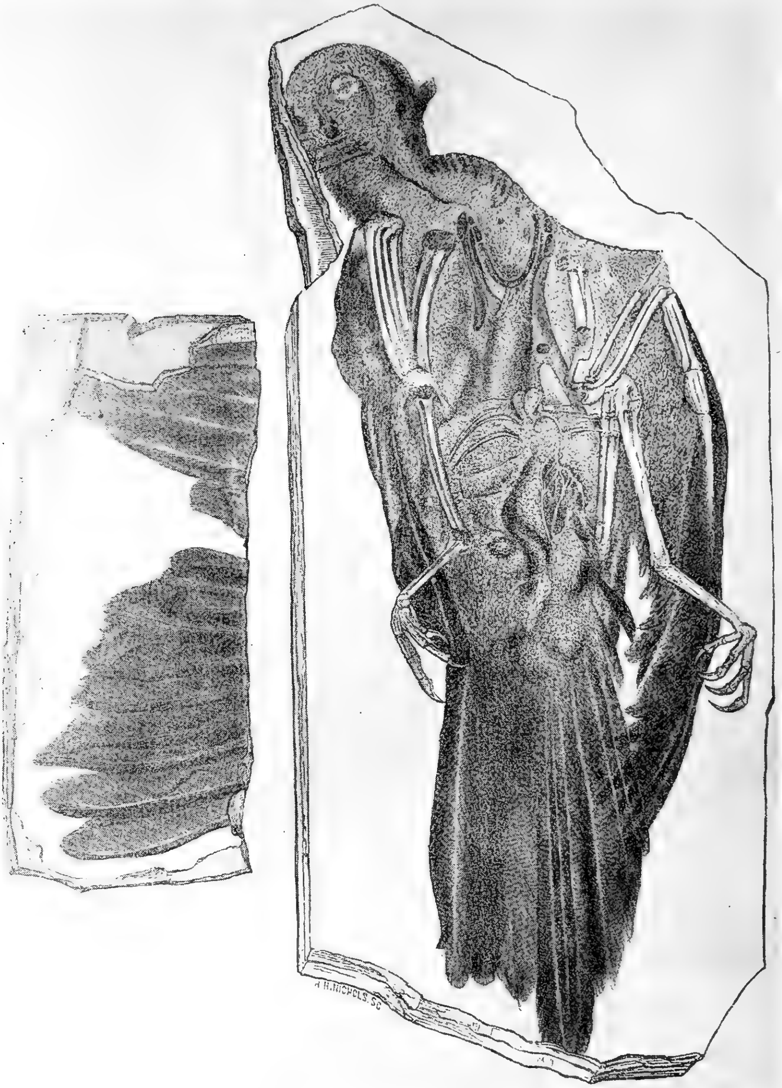

FIG. 8.—*Palaeospiza bella* Allen. By the author after Dr. J. A. Allen's figure. Somewhat reduced. The additional slab to one side is of Fig. 2 from Allen's paper, which he suspected belonged to another specimen. (Fully referred to in the text of the present paper.)

feather, with the shaft and vane in excellent preservation."[1] This specimen I have never seen, and I am unable, at the present writing, to say where it is deposited.

Very fine, as well as large, fossil feathers of birds—and most perfectly preserved—are also found in various parts of Europe; one of these is here shown in Fig. 7, it having been photographically copied by me from Tab. I to a most valuable article on fossil birds, which appeared a year ago in the official publication of the Königlich Ungarische Ornith. Centrale, a copy of which was kindly sent me by its author.[2]

On the fourteenth of June, 1913, Dr. Charles Schuchert, curator of the Geological Department of the Peabody Museum of Natural History of Yale University, sent me for description a number of fossils, most of which were of birds and birds' feathers, and all of the last two are utilized in the present article.[3]

Fig. 9 shows a large fossil feather that evidently belonged to a bird of considerable size. It is one of those sent by Dr. Schuchert, and was probably found at Green River, Wyo. (Cat. No. 1227). It is the distal extremity of the feather—about 65 mm. of it—showing the shaft and the soft vanes on either side, the latter being somewhat disturbed proximally. This structure is of an extremely delicate character, and, if really a bird's feather, it was of the

[1] O. C. Marsh, *Amer. Jour. Sci. and Arts*, 2d ser., Vol. XLIV (1870), 272.

[2] Koloman Lambrecht, "Fossil Vögel des Borsoder Bükk-Gebirges und die Fossilen Vögel Ungarns," mit 4 Abbildungen und 4 Tafel-Beilagen. Separat abdruck aus dem XIX Bande der *Aquila*, 1912, pp. 270–320. This paper contains descriptions of a large number of fossil birds from the region in question, most of them, if not all, being species still to be found in the avifauna of the Continent.

[3] Dr. Schuchert remarked in his letter of transmittal:

> We are sending you today by express, prepaid, a small box containing all of the fossil feathers that we have. On one of the slabs you will also notice two feet of a bird, and in another box there are quite a number of bird bones that were sent Professor Marsh many years ago by Professor Condon. You are at liberty to make use of these feathers in any way you see fit. Should you illustrate them or apply names to them, please place such information with the specimens, so that we may make the proper entries upon our records.
>
> The two fine specimens of *Archaeopteryx* I saw some years ago in Europe, and of course these are by all means the finest cases of preservation of bird feathers. There is at least one other occurrence of a bird feather from the Solenhofen Upper Jurassic, and I rather anticipate there might be more if you would make extensive inquiries in Europe, particularly in Munich. I have looked through Professor Marsh's correspondence and find nothing there in the way of information concerning our specimens other than that given on the labels.
>
> Hoping you are well, I am,
>
> Yours truly,
>
> [*Signed*] CHARLES SCHUCHERT

FIG. 9.—Large fossil bird feather. "Probably from Green River, Wyoming." No. 1227, Peabody Museum of Natural History, Yale University. Photograph of specimen by the author.

semi-plumulaceous kind. This specimen is upon a very thin slab, as may be observed in the figure. There is another faint indication of a small feather upon it, and a nondescript little fossil near the opposite border. It would be impossible to make a correct reference for this specimen or even to predict to what family the bird belonged that possessed it.

Many large birds, belonging to very diverse groups, probably flourished at the time, and it may have belonged to almost any one of them, as those I have in mind would all have feathers, in certain parts of their plumage, something after this order.

Among the material sent there is still another bird's feather of this character from the same locality (No. 1226, Peabody Mus. Nat. Hist.) that I have not figured in this article. No doubt can exist with respect to this being a fossil bird's feather, and one from a rather large bird of some species I am quite unable to determine—evidently one of the large wing-feathers; it shows the distal 70 mm. of it—the vane being, on an average, some 30 mm. transversely. This fossil, or perhaps its impression, is very faint and delicate, the surface of the matrix being almost smooth and flat. It will not be possible to state correctly to what kind of bird this feather belonged; but it may be said in passing that it resembles very closely the feather shown in Fig. 9.

Another slab (No. 1230) has a somewhat faint and feathery fossil upon it that may represent rather large plumulaceous feathers; but they may not be, and I would not care to undertake to decide the point. On the other side of this slab there is a partially broken-off skeleton of a medium-sized fossil fish (No. 861)—a fact mentioned merely to assist in the identification of the slab in the collection hereafter; it is from the same Green River beds of Wyoming, and the character of the thin slab is the same.

Other undeterminable feathers are shown in Figs. 11 and 12 of the present paper (*d*, *e*, and *f*, and *d′*, *e′*, and *f′*). Their museum numbers, the collectors, the beds and localities from whence they came, are, with other data, fully described in the figures throughout this article. In Fig. 12, I strengthened the fossils by pen and india-ink to give their outlines better. Nothing definite can be given about these as they are altogether too fragmentary and faint.

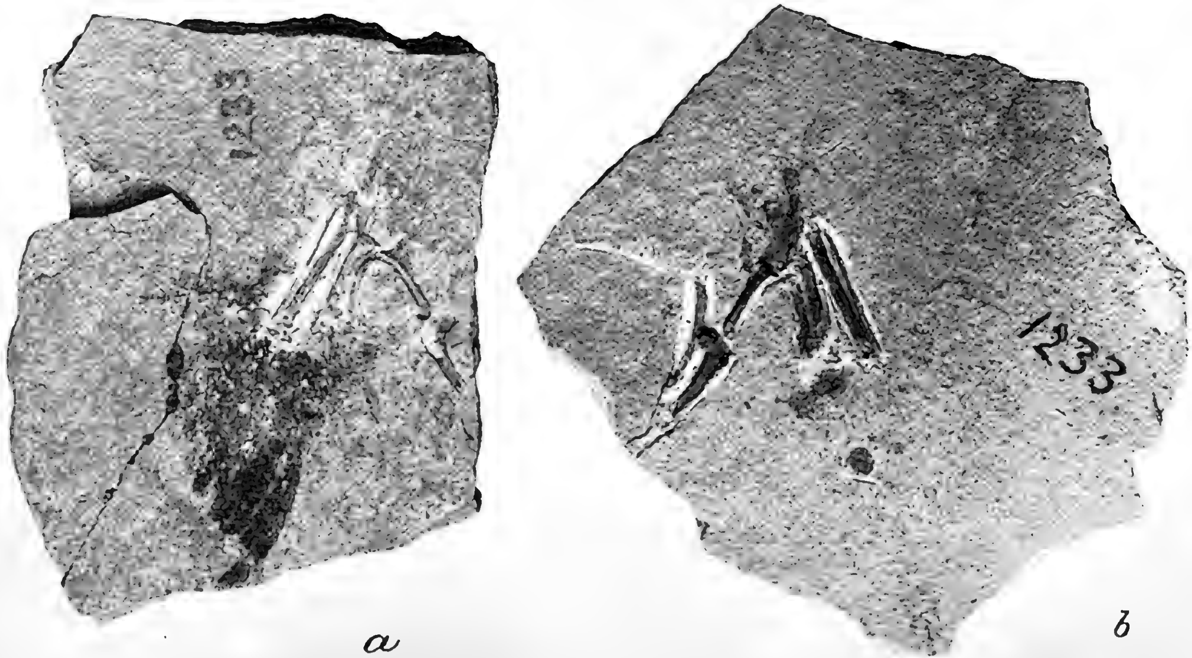

FIG. 10.—*Hebe schucherti*. Natural size. Reproductions of photographs direct from the specimens by the author. No. 1233, Peabody Museum of Natural History, Yale University. Found five miles west of Green River City, Wyo., in the fish cut of the railroad. Found by F. C. A. Richardson of Chicago (1874), with Powell Expedition. It was associated with insects described by Professor Scudder. *a*, slab showing the feathers and impressions of bones. *b*, slab containing fossil bones.

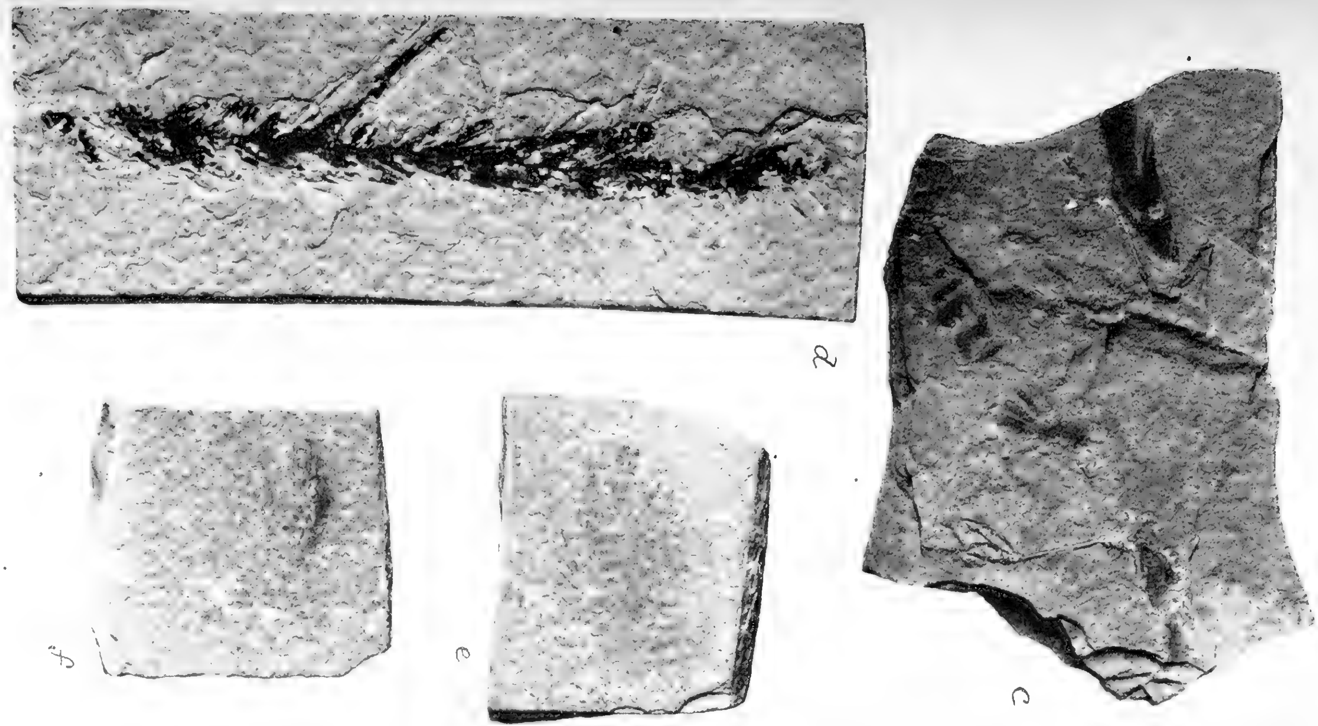

FIG. 11.—*Yalavis tenuipes.* *c*, No. 1231, Coll. Peabody Museum of Natural History, Yale University. (Marked "Bird" January, 1876, by Professor O. C. Marsh.) No further history. Natural size. Photograph by the author. (See Fig. 12, *a*, *b*, *c*, and *d*.) *d*, fossil feather of bird. Orig. No. 988, Cat. No. 1235, Coll. Peabody Museum of Natural History, Yale University. From Green River beds (Eocene). Coll. A. Schoonmaker. Found near Evanston, Wyo. Received July 31, 1877 (see *d'* of Fig. 12). *e* and *f*, two slabs of same specimen. Fossil bird feather, distal portion. Coll. Peabody Museum of Natural History, Yale University. Orig. No. 1013. Cat. No. 1228, Coll. A. Schoonmaker, Bear Lake Valley, Wyo. Came in lot of fishes sent Professor Marsh. Natural size. Photograph by the author. (See Fig. 12.)

The two feathers shown on the slab containing, at least, the pedal remains of the fossil bird described farther on in this paper in all probability belonged to the specimen. One of them is evidently a contour feather (Fig. 12, *c*), and the other from a wing (Fig. 12, *d*).

Similar feathers or feather impressions are also to be seen on other slabs at hand, such as those figured in Fig. 10 (*a*), in Figs. 3 and 4, and an unfigured one (No. 1232, Peabody Mus. Nat. Hist., Green River, Wyo. From F. V. Hayden) which I am very much in doubt about, as it so closely resembles some of the bits of fossil ferns shown me recently by Dr. Knowlton.

I now pass to the descriptions of the slabs belonging to the Peabody Museum, which contain the fossil remains of small birds heretofore undescribed. These are fully recorded in Figs. 10–12, where the required museum data are set forth. Two such birds are at hand, or rather fossil parts of them; these latter both belonged to small passerine species, and are more or less perfect, as far as they go. These parts, however, are not sufficient to admit of referring either of these birds to the genus to which it belonged. This being the case, I have thought it best simply to give them names by which they may hereafter be known, in order that avian paleontologists may be aware of their existence and of the museum to which they belong.

They may or may not have been from specimens representing genera still in existence in our avifauna; if they are, the generic names may be changed when future material is found, to which some paleontologist, in the years to come, can refer them with *absolute certainty*. As to the specific names, which I have given them below, they will stand for all time, as there is not enough of this material ever to decide upon that point with unqualified correctness. With these few words of explanation, I am sure it will be useful to future researchers in this field to have names attached to these specimens, in that they may be used and referred to in making other studies and comparisons.

Hebe schucherti, gen. et. sp. nov.

(Fig. 10, *a* and *b*)

The specimen is upon two slabs, one giving the actual bones found (*b*), and the other their impressions with some of the feathers of the wing—apparently the *right* wing.

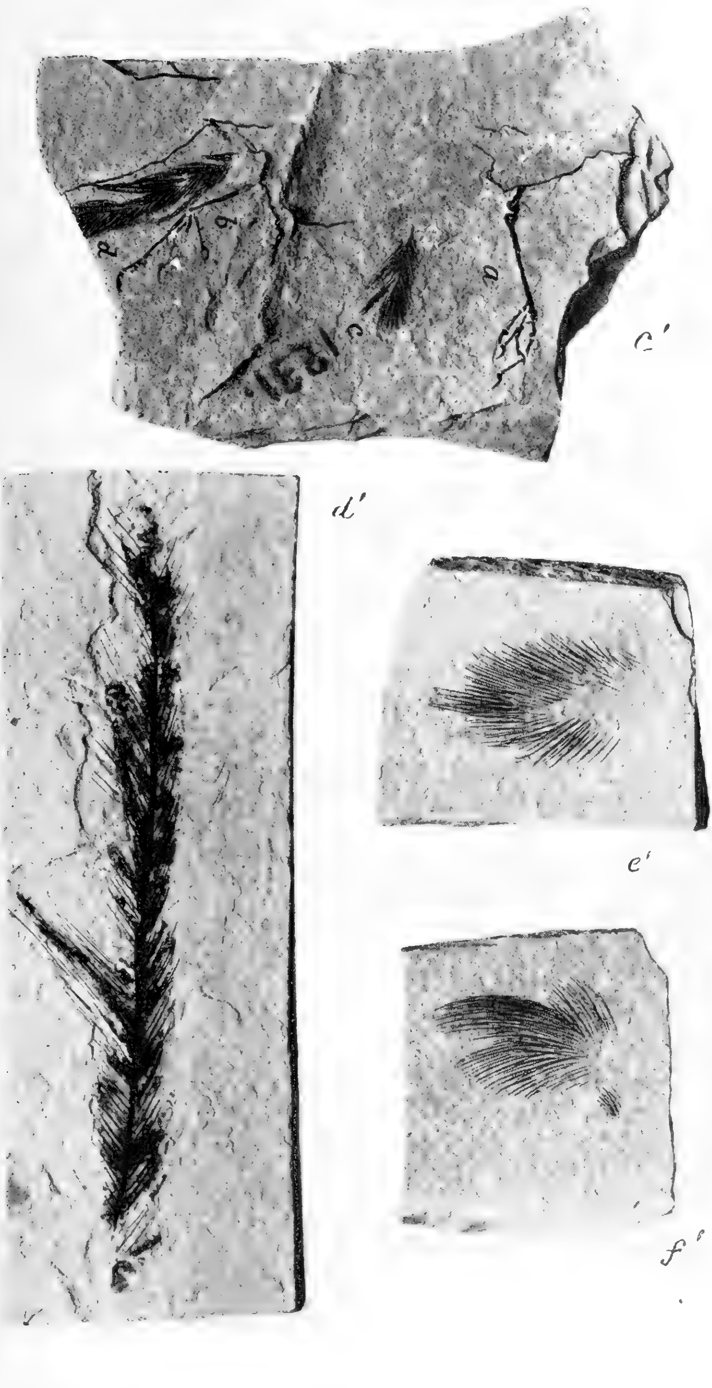

Fig. 12.—*Yalavis tenuipes*. Duplicate of Fig. 11 (see *antea*). Structures to be seen (Fossil) made black by the author, who also made the photographs direct from the specimens. $c' = c$ of Fig. 11, a and b (on the slab), fossil feet; c and d (on the slab), fossil feathers. $d' = d$ of Fig. 11; $e' = e$ and $f' = f$ of Fig. 11. Natural size. Same history as given under the previous figure (Fig. 11).

At this writing, the specimens are in the collection of the Geological Department of the Peabody Museum of Natural History, Yale University (Orig. No. 2831, Mus. No. 1233); found five miles west of Green River City, Wyo., in the fish cut of the railroad. Collector, F. A. C. Richardson (1874), Powell Exp. It was associated with insects described by Dr. Samuel H. Scudder.

On the other side of the label accompanying this material, apparently in the same handwriting, I find: "Compare *Pteroptochidae;* see *Ibis*, 1874, p. 19 (July), for sternum with 2 emarginations in *Sternum.*" This will be commented upon farther on.

The slabs are light colored and *thin*, and I have so arranged them in Fig. 10 that the fossil bones (*b*) and their impressions (*a*) bear the relation to each other that they would have had they been on the opposite pages of a book, and we had opened it to examine it.[1]

The bones on the slab *b* are as follows (and the *impressions* of all of them are seen on the slab *a*, which, with but one or two exceptions, are brought out with marked distinctness):

1. The *sternum* (in part: ventral aspect).
2. Both *coracoids*.
3. *Os furcula*.
4. A *scapula* (left).
5. *Humerus* (left: proximal moiety).
6. *Ulna* (right: nearly perfect).
7. *Radius* (right: nearly perfect).
8. Bones of *manus* (right: very faintly indicated, and some not exposed).

The feathers have already been referred to in a previous paragraph.

This skeleton belonged to an adult bird about the size of a cactus wren (*Heleodytes*).

The sternum.—Upon very close and careful examination with a high-power lens, we are enabled to observe the fact that the posterior margin of the sternum of this bird possessed two notches upon either side of the keel or carina; there is just enough of the bone

[1] On the opposite side of the slab (*b*) there is a small fossil fish, lacking three-fourths of the fore part of the skull; approximately, it had an extreme length of about 76 mm.

in sight to make certain of this.[1] It is the right side of the body of the bone that is exposed in the specimen; and, as its posterior border had *four* notches—that is, two on either side of the carina—the *sternum* of that bird differed in this particular from all *typical existing* passerines as they now occur in North America, at least north of Costa Rica.[2]

Many years ago, in speaking of the *Pteroptochidae*, Sclater pointed out that this assemblage "must remain, therefore, as an independent family of themselves, to be placed, according to my views, at the end of the Tracheophonine section of the Passeres, and at once distinguishable from all other Passeres by the posterior margin of the sternum being doubly emarginated as in the *Pici* and many *Coccyges*."[3]

That this bird was a passerine species with a four-notched sternum, and not a cuckoo or a woodpecker, is at once evident when we come to examine the remainder of that bone, and find that it possesses a large manubrium which is *bifurcated* anteriorly, thus producing two diverging apophyses, as is the case in the sternum of any true passerine form.[4] This sternum has a mesial length

[1] See note above (on original label) in regard to sternum of the *Pteroptochidae*.

[2] I have not examined the sternum in *Scytalopus argentifrons* of Costa Rica (see Ridgway, *Proc. U.S. Nat. Mus.*, XIV [1891], 475; Sharpe, *Hand-List*, III, No. 13, p. 5). Possibly it may have a four-notched sternum; but there is no material at my hand either to prove or disprove it.

[3] P. H. Sclater, "On the Neotropical Species of the Family *Pteroptochidae*," *The Ibis*, 3d Ser., No. XV, July, 1874, Art. XXIII, p. 191 (Plate VIII), of *Rhinocrypta fusca*. "The only other known Passerine form in which two emarginations are present on each side of the posterior margin of the sternum is the Australian genus *Atrichia*. Whether this form certainly belongs to the *Pteroptochidae* cannot be positively ascertained until the structure of its larynx is known; but I have little doubt that such is the case. There is a sternum of *Atrichia rufescens* in the Cambridge Museum."

To this I may add that on this date (July 1, 1913) there is not an alcoholic specimen, nor a vestige of a skeleton of any of the species of the *Pteroptochidae* in the collections of the U.S. National Museum for anatomical examination.

A. H. Garrod presented a sternum of *Hylactes megapodius* to the Museum of the Royal College of Surgeons of England; but I have never seen the specimen (S.S. 2660) (*Cat. Mus. R. Coll. of Surg. of Eng.*, 1891, p. 123).

[4] R. W. Shufeldt, Fig. 58 in *Key to North American Birds* (Vol. I, E. Coues, 5th ed., p. 151). This figure gives a ventral view of the "typical passerine sternum of the robin (*Planesticus migratorius*)," and in it the bifurcations of the manubrium of the bone are well shown.

of 15 mm., measured from the median anterior point of the posterior one on the carina.

A *coracoid* is 11 mm. long, being considerably expanded below, and developing a small process at its outer sternal angle. The bone is straight, and otherwise presents the usual passerine characters.

The *os furcula* is of uniform caliber with respect to the clavicular limbs, and not especially stout. It is of the broad U-shaped form, with the hypocleidium (if present) not exposed.

A *scapula* appears to be somewhat slender, though rather dilated and curved outward, distally. It has a length of about 11 mm.

Only a part of the left *humerus* is preserved in sight, and this exhibits some of the effects of pressure; it presents nothing worthy of especial note.

Passing to the *radius* and *ulna* of the right arm, we find them in a beautiful state of preservation, and in plain sight. They are quite straight bones, especially the *ulna*, which has a length of about 20 mm.

Bones of *manus* are not sufficiently exposed to admit of examination.

Whether the fossil bones of this bird belonged to a species of a genus in the *Pteroptochidae*, I am not at this time prepared to say; though as far as the evidence goes, there is every indication that it did—that is, barring the present range of those birds which, with one exception, is South American.[1] However, as I found a *flamingo* among Oregon fossil birds, it should not now be a source of surprise were we to meet with the fossil remains of a small South American passerine in the Green River deposits of Wyoming; the climate was entirely different at that age in North America.

It is not likely that this species belonged to any of the existing genera, and I have therefore created a new genus to contain it,

[1] "*Pteroptochidae:* A South American Family of formicarioid passerine birds, typified by the genus *Pteroptochus*, with tracheophonous mesomyodian syrinx, taxaspidean tarsi, operculate nostrils, and ten primaries; the rock wrens. They are small, wren-like birds of skulking habits, especially characteristic of Chile and Patagonia.

"There are about 24 species, leading genera of which, besides the type genus, are *Hylactes*, *Scytalopus*, and *Rhinocrypta*. Some of them are known as 'barking-birds'" (*Cent. Dict.*, p. 4826).

the same being provisional, or until such time when we have more material of both fossil and existing forms wherewith to critically compare it.

Hebe (new genus), the goddess of youth and spring of Greek mythology.

The specific name is in honor of the eminent paleontologist of Yale University, Dr. Charles Schuchert.

Yalavis tenuipes, gen. et sp. nov.

(Fig. 11, *c*; Fig. 12, *c'*)

From a study of the figures in the illustrations (fossil bones, etc.) it will be seen that in Fig. 12 (*a*) the specimen consisted of parts of the *left* pelvic limb, being the lower part of the tibio-tarsus; the tarso-metatarsus, and the toes complete. It is of the left limb for the reason that these are the actual bones, and the *inner toe* is to the outer side—that is, the first in order as we examine the foot.

It belonged to a small *passerine bird* of about the size of any one of the North American warblers, such, for example, as the pine warbler (*D. vigorsi*) or a somewhat larger species. The *tarso-metatarsus* has a length of 15 mm., and is, together with the toes, of notably *slender* proportions.

The toe-joints can be easily measured in the figures, as they are exactly of natural size.

The *right* foot of this specimen is doubtlessly to be seen at *b* on the same slab (Figs. 11, 12). Here the phalangeal joints occupy different positions.

These bones belonged to some small passerine bird that cannot as yet be referred to with certainty.

Birds of the same genus and species may or may not be still in existence; the probabilities are that they are not.

This specimen indicates that it belonged to a highly specialized *perching* bird, with very much *curved* claws, and the claw of hallux *not* lengthened as in the larks and their allies.

When we come to consider the vast number of small *passerine* birds that are in existence at the present time; and how many more there may have become extinct, representing such scores of

families, many species of which would possess the skeletal parts of the foot of a size and proportion quite like the one in this fossil, it will be appreciated how useless it would be to express an opinion as to the *family* this bird represented. No such attempt will be made here.

My reasons for creating a new genus for it are set forth on a foregoing page of this article.

Yalavis (Yale and *avis;* the University at New Haven, Conn., U.S.A.; and *avis*, a bird).

The specific name *tenuipes* refers to the slender bones in the foot of the specimen, as seen in its fossil remains.

Early in the summer of 1913, Mr. Theo. D. A. Cockerell, of the University of Colorado (Boulder, Colo.), when on a visit to Washington, handed me the specimen, here reproduced natural size in Fig. 3, for a description and, if possible, a diagnosis.

As the specimen is very small, I had it enlarged, and this latter is reproduced in Fig. 4.

It has no special history beyond having been collected in 1898 at Florissant, Colo.

At first glance, it has the appearance of being the fossil remains of some small bird, or even medium-sized bird, as it is associated with a few feathers. The latter consist of down (?), contour feathers, and one feather from a wing. The bones, whatever they may be, are in *pairs*, and evidently not materially disturbed.

By the aid of a two-inch objective on a powerful microscope, I brought these up to a large size for critical examination. To some extent they appear as though they might be a pair of *coracoids* and some part of the *sternum;* but as here exposed, I find that this suggestion cannot be verified.

It may be some part of a bird's skull; the smaller pair of bones, *pterygoids*, and the larger ones—partly exposed—*palatines;* but I doubt it. And were this so, the feathers would probably have belonged to the *head*—a fact militated against by the presence of what is undoubtedly a *wing-feather*.

These bones may have belonged to some other animal than a bird, or it may even have been some invertebrate form (crustacean), and the association with feathers entirely coincidental, as we would

find the fossil bones of some small mammal mixed up with, or in the same matrix associated with, those of some large raptorial species of bird that had eaten it just prior to its death. Such a case I have recently had good reason to suspect.

Pressure, fracture, and a number of other causes have caused fossil bones of animals of all sizes (vertebrates) to change their form and appearance. This must be borne in mind when making examinations of such material as we have here.

Then, when incased in a matrix and only *partially* exposed, bones have a very different *appearance* from what they have when seen in entirety. Every paleontologist of experience is aware of this fact.

Let us imagine that the fossil base of the superior mandible of a male surf scoter (*Oidemia perspicillata*) was the only part exposed in a dense matrix; would anyone suspect it of being a *duck?* When some bones are but partially exposed in the matrix, they often resemble others of the skeleton when the latter are more fully in view. For example, we may so far immerse the distal end of some avian *humeri* that the part left exposed may, in some instances, very much resemble the coracoid of some other kind of bird; and there can be no end to such instances.

This may easily be the case with the specimen here being discussed. The larger pair of bones seen in the enlargement in Fig. 4 may be the proximal extremities of a pair of humeri, palmar aspects, and only partly exposed, and the small pair (?) below them some part of a dorsal *vertebra.* It is quite possible.

In short, I am of the opinion that a reference—a correct reference—cannot be made for this specimen, beyond its being probably *bird*, and under the circumstances it would be useless to give it a name.

The fossil bird bones from Silver Lake, Ore., mentioned in Dr. Schuchert's letter on a previous page of this article, are, in all particulars, like those belonging in the Cope collection of the American Museum of Natural History of New York City. Very recently I have fully described that entire collection, and this description will appear as a bulletin of that institution with upward of 600 figures on plates.

The specimens now before me can be compared with those figures, thus rendering any description of them here superfluous.

It may be said, however, that in the lot now before me I find two *cervical vertebrae*, probably of an adult female of the western grebe (*A. occidentalis*); a portion of the right ramus of the mandible of some species of duck (?); bits of shafts of long bones (*humeri*, *ulnae*, *radii*, etc.), not determinable; a toe-joint, and the distal end of a *tibio-tarsus* (No. 1236), not determinable with certainty; a ray from the pectoral fin of a fish, proximal extremity—a bone also discussed in my forthcoming memoir.

THE VOLCANOES AND ROCKS OF PANTELLERIA

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PART I

INTRODUCTION

Since the first half of the last century, when Pantelleria[1] figured in the controversy over von Buch's theory of craters of elevation, the geology of the island has been described only by H. Foerstner and A. Bergeat. Through Foerstner's researches the island has become classic in the annals of petrography, because of his discovery there of soda-microcline and the peculiar hornblende, cossyrite, as well as of the occurrence of the remarkable group of pantellerites.

In view of the interesting character of its rocks and the rather early date of Foerstner's descriptions and analyses, a re-examination of the island was considered to be desirable. Pantelleria was, therefore, visited in September, 1905, in the course of a trip to the western Mediterranean, undertaken for the Carnegie Institution of Washington.

During my stay I met with the utmost courtesy and hospitality, and it is a pleasure to record my thanks to friends on the island, among whom may be specially mentioned Captain G. Herrera, Captain A. Pocobelli, Lieutenant A. Innorta, and Doctor S. Granone. To Professor J. Volney Lewis I am indebted for making the photographs of the rock sections.

GENERAL DESCRIPTION

The island of Pantelleria lies about midway between Sicily and Tunis, rising steeply from depths of over 400 fathoms in the broad, deep channel which separates Sicily from Tunis, near the edge of the Adventure Bank. It is noteworthy that the volcanic Linosa to

[1] Attention may be called to the fact that this is the proper spelling of the name, being that used on all the official Italian maps. The chief accent is on the *i*, not the second *e*.

the southeast rises out of the same channel and is surrounded similarly by deep waters, while the neighboring limestone islands of Lampedusa and Malta are inside the hundred-fathom line, on the edges of the shallow banks which border, respectively, the east coast of Tunis and the south coast of Sicily.

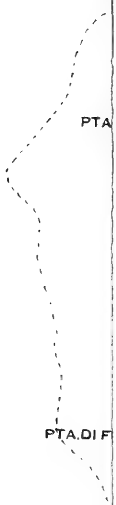
The island is elliptical in shape, with a length of about 13.5 kilometers from northwest to southeast, a breadth of about 8 kilometers from northeast to southwest, and an area of 33.3 square kilometers. Seen from the sea it presents a roughly mountainous and forbidding appearance, which is increased by the prevailing dark color of the rocks, so that it is often spoken of as "L'Isola Nera," the Black Island.

HISTORY

Pantelleria was inhabited in prehistoric times by a people of unknown race, who have left traces of their occupation in the peculiar constructions which are known as *sesi*, found only in the northwestern part of the island (Fig. 1). These are built of rough blocks of lava and are shaped like an elongated dome with a length of 40 to 50 feet, a width of about half this, and a height of from 15 to 25 feet. Each contains several small chambers, separate from each other, and entered by a rather small opening near the ground. In many respects they are almost unique, but they show some analogies with the *talajots* of the Balearic Islands and the *nuraghi* of Sardinia. These latter, however, are better constructed and far more elaborate, and evidently belong to a higher type of civilization than that of Pantelleria.

The island was known to the Greeks, who called it Κοσσοῦρα (Strabo), Κοσσύρα (Ptolemy), and other variants, while the Romans named it Cossyra (Ovid and Pliny), Cossyrus (Silius Italicus), Cosura (Seneca), etc. The origin of its present name, which dates from about the fourteenth century, is unknown, and its etymology uncertain. Its history has been briefly sketched by D'Avezac,[1] who, however, does not mention the *sesi*. According to him it was probably first inhabited by the Phoenicians or Carthaginians. Traces of this remote occupation are still to be found in the dialect

[1] D'Avezac, *Iles de l'Afrique*, Paris, 1885, p. 104.



MAP OF PANTEL

SCALE 1 : 64,0

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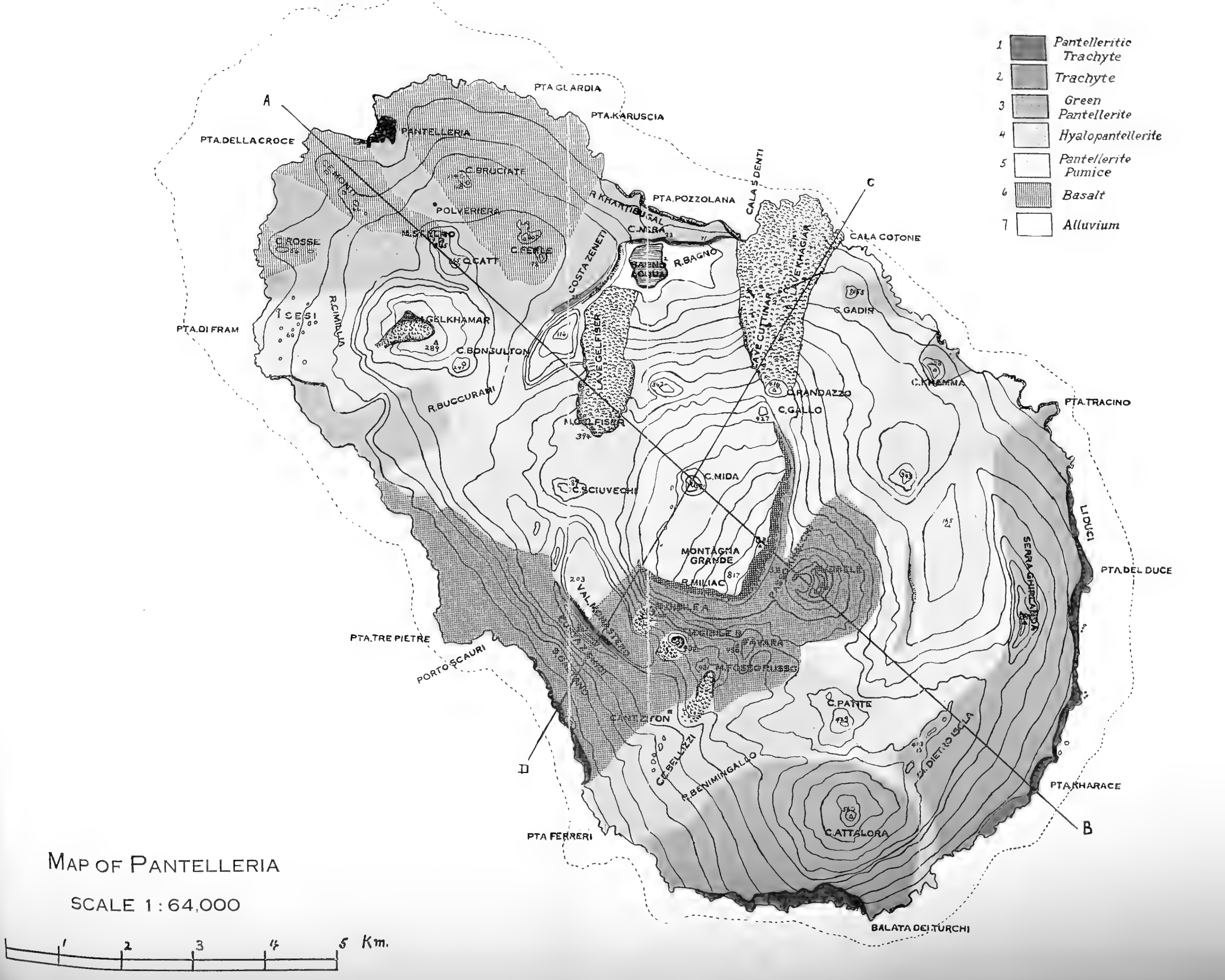

MAP OF PANTELLERIA

SCALE 1 : 64,000

1 2 3 4 5 Km.

and in many of the topographic names. From this Semitic period dates a coinage which Head[1] refers to the second century B.C. Cossyra figured in several episodes of the Punic wars, but on the fall of Carthage became Roman, and another series of coins dates from this epoch.[1] It seems to have had a reputation for roughness and inhospitality and is mentioned by Seneca as one of the most undesirable places of exile.

FIG. 1.—Sese (prehistoric dwelling)

It was captured by the Moors in 835 A.D., who called it Qussra, a name by which it is still known in Arabic. After a stormy period, during which the island was the object of contention between the Moors and the Norman kings of Sicily, it became part of the kingdom of Sicily, and thence passed under the dominion of the present kingdom of Italy.

PRODUCTS AND POPULATION

The cultivable parts are mostly given over to vineyards, which produce large, white, and very sweet grapes, which are dried to

[1] Barclay V. Head, *Historia Numorum*, London, 1887, p. 743.

form raisins of a most excellent quality. These vineyards are terraced and surrounded by high stone walls, thus concealing the geology of the areas covered by them. Capers are also cultivated, growing abundantly over the stone walls, while excellent donkeys, noted for their strength and endurance, form the third principal object of export. Olives and figs are also raised.

The island is subject to violent winds, so that fig trees often grow with their trunks horizontal and close to the ground. Vegetable gardens and the small groups of fruit trees are usually protected by high, circular, surrounding walls, such inclosures forming a characteristic feature of the landscape in parts of the island.

Potable water is very scarce, though it is furnished by some of the volcanic springs, one of which forms a public fountain in the town. This is closed except for an hour every morning, when each household is allowed to draw its allotted supply. Some of the steam fumaroles are utilized by herdsmen by covering them with brushwood, which condenses the water and gives rise to small rivulets. The rains are the main source of supply, the water being gathered on the flat, cemented roofs and preserved in cisterns beneath the houses. But after a long dry spell, as at the time of my visit, this supply is likely to fail and the whole population goes on short water rations. Indeed, at times, water has to be imported from Sicily, and an earthquake is likely to cause great distress by cracking the cisterns, as happened prior to the submarine eruption of 1891.

The population numbered 8,619 in 1901, of which about 2,500 inhabit the sole town, also called Pantelleria, on the northwest coast. There is an evident infusion of Moorish blood, dating back to the Saracenic occupation, or even possibly to the original Phoenician settlement. This is specially manifest in the island dialect and in the place-names, many of which show distinctly non-Italian forms, and some of which can be positively identified with Semitic roots. Thus Gibelé is clearly the Arabic جبل (*gebel*) = "mountain,"[1] and Rione Ziton is from زيتون (*zitun*) = "olive," Khagiar is derived from the Arabic حجر (*hajar*) = "stone," Gelfiser probably from جبل فزر (*gebel fozir*) = "burst mountain," Gadir

[1] The same is seen in the name Mongibello for the peak of Etna, and an analogous case is the peak of Ὄρος Βοῦνο (Mountain Mountain) on Aegina, Greece.

possibly from غدير (*ghadir*) = "a pond," and Gelkhamar from جبل قمر (*gebel kamar*) = "moon mountain." The local term *cuddia*, applied to the small volcanoes and hills, may be derived from حاد (*hadd*) = "pointed;" and if so, its etymology would be analogous to that of the French *puy* and the Catalan *puig*.

Pantelleria is now used by the Italian government as a penal station (as is Lampedusa), several hundred convicts being at liberty on the island, returning to their quarters at night, and being guarded by two companies of soldiers.

TOPOGRAPHY[1]

Montagna Grande.—The most prominent topographic feature of Pantelleria is the volcanic mass of Montagna Grande, which occupies the center of the island, its summit forming the culminating point with an elevation of 836 meters above sea-level. The mass has suffered extensively from erosion and shows few traces of the original crater. The top consists of a ridge on the east and south, from which the surface slopes rather gently downward toward the west and north. On this slope is the cone of Cuddia Mida, with a small summit crater, so called from being near the center of the island. The summit ridge of Montagna Grande is very precipitous outwardly on the east and south, the scarp varying from 50 to 150 meters in height, built up of massive sheets of trachyte, which sometimes show a rough columnar structure. These scarps do not form a continuous curve, but are roughly straight lines, meeting at an angle of about 110° at the southeast corner at Rione Miliac. From their foot the surface slopes sharply downward to the south and east, the general uniformity being interrupted by several small volcanic cones.

Of these Monte Gibelé, immediately east of the highest point of the summit ridge, is the largest and most important. It is fairly well preserved, its highest point being 700 meters above sea-level, and it shows an almost circular crater, about 100 meters deep and

[1] The accompanying map is based on that of the Instituto Geographico Militare (Firenze, 1877, 1:10000), the geology being based on the map of Foerstner (*Bull. Cour. Geol. Ital.*, 1881, Tav. XI.), and my own observations. The contour lines (interval 50 meters) are only roughly given, and the boundaries of the different geologic areas are only approximate.

200 meters across, which is breached on the southwest side. To the east and southeast of Montagna Grande and Monte Gibelé is the long crescentic ridge of Serra di Ghirlanda, which runs parallel to, and about one kilometer from, the coast, and presents toward the Montagna Grande, over much of its length, a very steep face from 50 to 90 meters high. This is continued to the southwest in the curving line of the Cuddioli dietro Isola, a series of low, isolated hills. At the southwest end of this ridge, and occupying the southern end of the island, is the wooded cone of Cuddia Attalora, 560 meters high, a well-formed, very symmetrical cone, with the remains of a breached crater near the summit. The isolated Cuddia Khamma, northeast of Montagna Grande, appears to be a remnant of a continuation of the Serra di Ghirlanda to the north.

On the southwest and western flanks of Montagna Grande are several small, parasitic cones, namely Fosso del Russo, and two which are both called Monte Gibilé, and which may be designated as Gibilé *a* (north) and *b* (south), to distinguish them from the large cone of a similar name on the east flank. The southwest slopes of Montagna Grande run into the narrow, crescentic Valle del Monastero, which is about 2 kilometers long by half a kilometer wide. This is bounded on the west by the ridge of Costa Zichidi, which shuts in the valley with a precipitous scarp rising 30 to 75 meters above the valley floor. This ridge outwardly slopes rather gently down to the sea, the small harbor of Porto Scauri lying to the west of it and being used instead of the principal harbor when the wind is from the north.

The northwestern and northern slopes of Montagna Grande present a decidedly irregular topography, the original surface having been buried beneath the accumulations from several parasitic cones. Of these the most important are: Monte Gelfiser on the northwest, from which issued the flow called Lava Gelfiser, about 500 meters wide and 2,200 long, extending northwardly to near the Bagno dell' Acqua; and Cuddia Randazzo, on the north, with the large flow known as Lave Cuttinar in its upper portion and Lave Khagiar below. The total length of these is about 3 kilometers and they form a fan whose widest part stretches from Bagno dell' Acqua

on the west to Cala del Cotone on the east, a distance of 2 kilometers along the coast.

Rione di Bagno.—Close to the north coast is a small, irregularly elliptical plain, the Rione di Bagno (Fig. 2). The western part of this is occupied by an oval lake, the Bagno dell' Acqua, with dimensions of about 600 by 500 meters, the surface being only 2 meters above sea-level. The lake is shallow and is evidently the remnant of one which formerly covered the whole of the inclosed

Fig. 2.—Bagno dell' Acqua, from west

area. The Rione di Bagno (including the lake) is bounded on the west by the precipitous east face of a scarp, the Costa Zeneti, which rises to about 200 meters above the lake surface. This ridge is continued to the south and southwest, parallel to the course of the Lava Gelfiser, inclosing the narrow Valle Silhoumen, which is flanked on the east by the towering mass of tumbled lava blocks which constitutes the flow (Fig. 3). To the north the Rione is bounded by a similar though lower (38 m.) precipice, known as Cuddia Nera, which is indubitably a continuation of the Costa

Zeneti, the direction of the scarp face changing from north to east at the northwest angle of the lake. On the east are the rough masses of the Khagiar flow, and on the southeast and south the steep slopes of Costa del Bagno, evidently part of the original north flank of Montagna Grande, while at the southwest corner is the extremity of the Gelfiser flow.

Basaltic area.—The northwestern end of the island offers peculiar features of its own. In general the surface shows a fairly

Fig. 3.—Lava Gelfiser, from Costa Zeneti

uniform, gentle slope away from the central mass of Montagna Grande, the contour lines being roughly concentric about this. On this broad, low, conical base, which has a radial extent of about 4 kilometers and a maximum altitude in the interior of about 200 meters, there are several volcanic cones. These are of two distinct types—a pantelleritic and a basaltic.

Of the former type is Monte Gelkhamar, whose summit, 289 meters above sea-level, rises not more than 100 meters above the general slope on the east, but about 200 meters on the west. In form it is roughly circular, though somewhat irregular, and is

notable for the large barranco which has breached the southwestern side, forming an impressive gulf 600 meters long and 300 wide, with precipitous sides. From this issued the lava flow of Rione Cimillia, on which are to be found the prehistoric buildings mentioned above. The second pantelleritic cone lies about one kilometer north-northeast of Gelkhamar and one and a half south-southeast of the town of Pantelleria. It is crescent-shaped, widely breached on the east, the ridge culminating in the northerly Monte Sant' Elmo (245 m.), on which is a semaphore, and the southerly Cuddia Catt (265 m.). The main mass of this is composed of pantellerite, but on the north flank of Sant' Elmo there has taken place a small, later eruption of basalt, the scorias and lavas of which cover the northern and western slopes, while a flow extends to the north.

The basaltic cones, which are entirely confined to this part of the island, are all small and are less important topographically than they are petrographically. The best preserved are the Cuddie Brucciate and the Cuddia delle Ferle, respectively one and two kilometers southeast of Pantelleria. The former consists of a twin pair of cinder cones, with summits 118 and 114 meters above sea-level, but only about 30 above the base, each with a deep, circular, well-preserved crater. Cuddia Ferle is somewhat higher (207 m.), but with a less well-marked summit crater and with a small subsidiary conelet with breached crater on the north. On the northwest coast are the Cuddie Rosse and Cuddie delli (*sic*) Monti, which are 50 to 60 meters high. Flows of basalt and beds of scoria, derived in part from these cones and probably in part from now hidden vents, cover much of the northwestern coastal part of the island.

The coast line of Pantelleria is, in general, irregular with many small indentations. On the east, southeast, south, and southwest it is mostly precipitous, up to heights of 275 and 200 meters, due to wave action; while on the northwest it is low and formed by the tongue-like ends of the basalt flows.

GEOLOGY[1]

The geological structure of Pantelleria is somewhat complex and has given rise to divergent views. With the exception of some

[1] A short account by me of the geology of Pantelleria was published in *Science* (N.S.), XXVIII (1908), 576. It is practically an abstract of this section.

insignificant beds of travertine and the lacustrine deposits of the Rione di Bagno, the rocks are wholly volcanic. Some fragments of granite found by Foerstner[1] and Soellner[2] in several places on the island indicate that the foundation is of this material. I was not fortunate enough to meet with any of these, but observed fragments of diorite in the lava of the island of Linosa,[3] so that a basement of plutonic rocks may be inferred for the bed of this part of the Mediterranean.

Of the earlier view as to the structure, only mention may be made that Pantelleria was cited as an illustration of von Buch's theory of craters of elevation, the circle of scarps surrounding Montagna Grande being supposed to be due to elevation incident to the formation of this volcano.

Foerstner's views.—Foerstner has discussed the geological structure at some length.[4] In the following summary his rock-names will be retained. According to Foerstner the first eruptions on the granite base were of "phonolite" and "liparite," which uniformly underlie the other lavas, and which issued from a now vanished vent. These were covered by the "andesites" of Monte Gibelé, which was also probably the volcanic center of the lavas of Montagna Grande, then not raised to its present height. From an unknown center of the same epoch are supposed to have issued the "andesites" which form the surface of Costa Zichidi, and which are probably the latest flows of this stage. The next period was that of the eruption of the first pantellerites, especially of the crystalline variety, which poured out of numerous vents all around the large andesitic volcano. The Bagno dell' Acqua is supposed to belong to this period and to have been an explosion crater, while the Cuddia Attalora is a well-preserved parasitic cone of the same period.

The ejection of this mass of lava caused profound dislocations and resulted in the upthrust of the mass of Montagna Grande, which was accompanied by the formation of many subsidiary cones on its flanks and the pouring-out of flows of vitreous pantellerite, as

[1] H. Foerstner, *Boll. Com. Geol. Ital.*, 1881, p. 550.

[2] J. Soellner, *Zeits. Kryst.*, XLVI (1909), 522.

[3] H. S. Washington, *Jour. Geol.*, XVI (1908), 6.

[4] H. Foerstner, *Boll. Com. Geol. Ital.*, 1881, pp. 550–53.

represented by Monte Fosso del Russo, Monti Gibilé *a* and *b*, Monte Gelfiser, Cuddia Randazzo, and others. The faults according to Foërstner, are the cause of, and are represented by, the various encircling scarps mentioned in describing the topography and certain coastal features.

At the close of this period of dislocation the last of the pantellerite cones was formed, that of Monte Sant' Elmo and Cuddia del Catt, after which the lava underwent a change in composition, "by subtraction of silicic acid." The last phase of basaltic eruptions began with an outburst on the northwest flank of Sant' Elmo, and was continued in the small cones of basaltic scoriae and flows of basalt.

Bergeat's views.—The geological structure has also recently been briefly discussed by Bergeat,[1] who cites the mass of Montagna Grande as an example of *Staukuppen* or plug domes, analogous to the spine of Mont Pelée. He adopts the views of Foerstner that the prominent scarps are due to faulting, and indicates on a map the traces of what he considers to be the chief fault-lines, as shown by volcanic cones, scarps, or other lineaments. He calls attention, however, to the fact that a depression would more naturally be supposed to follow the ejection of lavas on a large scale than the upheaval advocated by Foerstner, and would explain equally well the formation of Montagna Grande and the precipitous scarps. On his view the upthrust of Montagna Grande is supposed to be a differential one, due to subsidence of the encircling portion. Bergeat considers that Monte Gibelé was the volcanic center for the whole mass of Montagna Grande and that the two were separated by a fault which he noted in the Passo Khalchi, northwest of the Gibelé crater. With Foerstner, Bergeat apparently considers the Bagno dell' Acqua as a separate center of eruption, since it is indicated on the course of one of his fault-lines, though he does not mention it directly.

Objections to these views.—I am quite in accord with Foerstner as to the general succession of the lavas, especially the earlier date of his "phonolites," "liparites," and the "andesite" of Zichidi, the subsequent eruption of the pantellerites, and the final appearance of

[1] A. Bergeat, *Neues Jahrbuch*, Festband, 1907, pp. 315–17.

the basalts; as I am with Bergeat's conclusion as to the essential structural unity of Montagna Grande and Monte Gibelé, and his conclusion that the latter was the crater of the "andesite" mass. My observations, however, lead me to different conclusions as to the presence of fault-lines and other lineaments, and the origin of the volcano of Monte Gibelé and Montagna Grande, the ring of scarps, and the Bagno dell' Acqua.

The straightness and parallelism of the supposed fault-lines of Foerstner and Bergeat appear to me, after examination of the island and study of the large-scale chart, to be unduly emphasized. As a matter of fact, the inner scarp and ridge of Serra di Ghirlanda with its orogenic continuation in the Cuddioli dietro Isola is far from being a straight line, curving gently round from a north-north-westerly direction at the north end, through north-south, to northeast-southwest at the southern end. A similar curvature is shown by the Costa Zichidi ridge, and also at that of Costa di Zeneti, which latter turns sharply, but without any tectonic discontinuity, into the ridge and scarp of Cuddia Nera, with an east-west direction. The scarp of the summit of Montagna Grande, on the other hand, while in general following the lines of the Ghirlanda–Zichidi ridges and facing them, shows essentially straight lines: one on the east with a nearly north-south direction and the other east-west, the two meeting in a sharp angle at the southeast corner of the mountain, at the Rione Miliac. On the west, northwest, and north, however, the mass of Montagna Grande shows no scarps which correspond to those of Costa Zeneti and Cuddia Nera. Furthermore, the eastern slopes of Monte Gibelé slope gently down, with typical volcanic cone topography, to the Piano di Ghirlanda, whereas if the Ghirlanda scarp was due to faulting, and if Monte Gibelé is an originally integral part of the Montagna Grande mass, as there is good petrographic and orogenic reason to believe, we should expect Gibelé also to show fault scarps marking the line of separation from the surrounding region.

Again, it is difficult to conceive of the origin of the deep and narrow valleys surrounding Montagna Grande on the basis of either the fault or the upthrust theory. The one would explain them by the slipping down or differential movement of narrow

blocks, concentric about the central mass, a case which, so far as I know, is unparalleled elsewhere, especially on so small a scale; or the other as due to erosion along the fault zone, which is also difficult to accept in view of the relatively dry climate and the character of the surface-drainage topography.

Without desiring to be polemical, I may mention that the fault-lines mentioned by Foerstner, and indicated on the small map by Bergeat, seem to me to be somewhat arbitrary and subjective and their apparent parallelism rather forced by judicious choice. Thus, the most northeasterly connects the Bagno dell' Acqua (which can scarcely be regarded as a volcanic center) with a very minor part of the Montagna Grande scarp. That on the southwest connects the very minor Cuddia Sataria with a not very pronounced part of the coast line. That connecting Cuddia Sciuvechi and Monte Fosso del Russo might have been extended on the one side to Cuddia Gelkhamar and on the other to Cuddia Attalora with little deviation from a straight line. Also, they are arbitrary in their omissions. Thus, radiating lines might have been drawn from Cuddia Mida as a center toward the north, northwest, and west, each of which would have run through three or more volcanic cones, and such radiating lines would have been consonant with the radiating system of dikes observed about many volcanoes.

Author's views.—Accepting the hypothetical granitic basement, which is in harmony with observations on Linosa, I suppose that the first volcano (which presumably started in submarine eruptions like those in 1831 and 1891[1]) was a large one and covered the whole of the present area of the island, except possibly a small area at the northwest. The flows poured out by this volcano were of pantelleritic trachyte (Foerstner's "phonolite" and "later andesite") and of comendite (Foerstner's "liparite"), the now existent sheets of which formed the lower flanks of the old cone. On the west, at the Costa Zichidi and the Scauri district, they still show in places traces of the original lava surfaces. Later than these, but issuing from the same volcanic center, which may be supposed to have been probably between the Cuddia Mida and Monte Gibelé, were flows of green pantellerite (Foerstner's crystalline pantellerites), which

[1] Cf. H. S. Washington, *Am. Jour. Sci.*, XXVII (1909), 131.

covered most of the slopes of the old cone and are now seen in the southeast portion of the island and to the north and northwest of Montagna Grande. This original, large volcano was reduced to a large caldera with an encircling somma (about 6 kilometers in diameter), with gentle slopes toward the periphery but steep scarps on the inner side, either by an explosion or possibly by subsidence of the central portion, according to Stübel's theory. These are the scarps of Serra Ghirlanda, Costa Zichidi, Costa Zeneti, and Cuddia Nera. A similar history and a similar form at the end of the first stage of activity have been true of many well-known volcanoes, such as Santorini, Monte Vico near Viterbo, Somma-Vesuvius, Etna, Pico de Teyde, Taal, and many others. During this first phase and presumably before the formation of the caldera there were formed the parasitic cones of green pantellerite, notably those of Cuddia Attalora, Cuddia Gadir, Monte Sant' Elmo, and Cuddioli dietro Isola.

The eruptions of the second phase began within this caldera, the floor of which may have been below sea-level (as in the case of Santorini), and which was apparently breached to the north, between Cuddie Nera and Gadir. These consisted largely of trachyte (Foerstner's "older andesite"), which built up the great mass of Montagna Grande and Monte Gibelé. I follow Bergeat in thinking that the latter served as the vent for most of these eruptions, while Cuddia Mida may be regarded as a later parasitic cone near the summit of the volcano, which emitted mostly pantelleritic pumice. The trachytes of Monte Gibelé filled, or nearly filled, the large caldera, and are covered in many portions of the area with pumiceous lapilli derived from Cuddia Mida.

This pumiceous outburst may be regarded as the last of this phase, after which the northwestern part underwent a serious dislocation. The block which constitutes the present Montagna Grande was separated from the Gibelé portion by the Passo Khalchi fault, and tilted about an almost east-west axis. The southern end was raised some 250 meters or so, forming the prominent Miliac scarp and bringing the upper edge above the level of the former summit of Monte Gibilé. To the north the movement was downward, producing the depression of the Rione di Bagno now in part occupied by the lake.

That such a movement can have taken place on the island is shown by that preceding the submarine eruption of 1891 near the corner of the island, when a section of the northeast coast from Punta Karuscia to Punta Tracion was raised nearly one meter.[1] Such a tilting of a fault block explains reasonably the steep scarps, their presence only at one end of the mass, the revealed structure of sheets of columnar flows, and the general slope of the surface toward the north, while the simple set of two almost straight lines formed by the scarps is also in harmony with this interpretation.

Subsequent to this dislocation the second stage of the second phase took place in the formation of the small parasitic cones of Fosso del Russo, Monti Gibilé *a* and *b*, Cuddia Randazzo, Monte Gelfiser, and others, which poured out flows only of black pantellerite (Foerstner's vitreous pantellerite). It is noteworthy that all these small cones are found on the edges of the Montagna Grande block, just where the movement of the block would give exit to the magma along the fracture lines. None of them have broken through the main area of the mass, though it is uncertain whether Cuddia Sciuvechi, which also poured out black pantellerite, is along the western fracture line or on the slope of the original large volcano, and hence belonging to Phase I.

The southern cones of this period, Gibilé *a* and *b* and Russo, are of small size, and their flows are short and barely do more than reach the bottom of the old caldera flow, not getting as far as the opposite inner somma ring. The northern cones, on the contrary, Cuddie Randazzo and Gelfiser, are much larger, and their flows of much greater length and volume, Khagiar reaching the sea and Gelfiser coming up to the Zeneti scarp and apparently overflowing the northwest corner portion of the tilted block. It will be observed that this disposition is in harmony with the structural explanation here suggested.

According to this interpretation the Bagno dell' Acqua (with the alluvial Rione) is not a center of eruption, as supposed by Foerstner and Bergeat, but part of the old caldera floor, somewhat lowered by the block tilting, and left uncovered by the flows of Monte Gibelé and those following the Montagna Grande dislocation. This

[1] G. A. Butler, *Nature*, XLV (1891), 584.

explains its features better than does the view that it is due to an explosive eruption, surrounded as it is by the scarps of Costa Zeneti and Cuddia Nera on two sides, and the ends of the lava flows of Gelfiser and Khagiar and the slopes of the Montagna Grande mass on the others.

With the cessation of the outflows of black pantellerite, though after what interval we do not know, began the phase of basaltic eruptions, the earliest being apparently that which broke through the green pantellerite of Monte Sant' Elmo. These were comparatively small in volume and confined entirely to the northwest part of the island, though Foerstner mentions some basaltic dikes as occurring along the east coast. These eruptions formed the small,

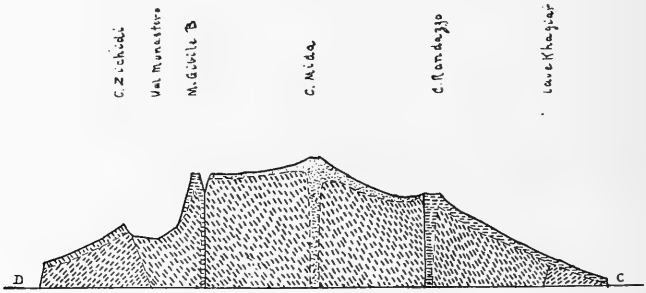

FIG. 4

scoriaceous cones already mentioned, and also gave rise to flows of basalt, which covered a large part of this portion of Pantelleria. The submarine eruption of 1891, four kilometers west of the harbor, is to be regarded as the last eruptive activity.[1]

Evidence of diminishing volcanicity is still manifest in fumaroles and hot springs. Of the former the most important are the Favara Grande and the Stufa di Khasen. The first is situated on the slope of Montagna Grande, northeast of Monte Fosso del Russo, at an altitude above sea-level of 410 meters. It consists of three openings in the rough lava, which emit scalding hot steam with a strong odor of sulphur dioxide, the rocks being deeply decomposed for some distance around. This fumarole is utilized by the goatherds for a

[1] H. S. Washington, *Am. Jour. Sci.*, XXVII (1909), 131.

supply of potable water by covering the openings with brushwood, which condenses the steam and gives rise to a variable trickle of water. The Stufa di Khasen is situated in the northwest corner of the island, near the Cuddie Rosse, and the vapors issue in a deep grotto, which was walled up and converted into a hot-vapor bath, apparently by the Arabs. There are other fumaroles below the Rione Miliac, at the summit of Montagna Grande, and in the crater of Cuddia Mida, as well as one, the Grotta di Bagno Asciutto, near Monte Gibilé *a*. The occurrence of these fumaroles around the Montagna Grande block is quite consonant with the presence

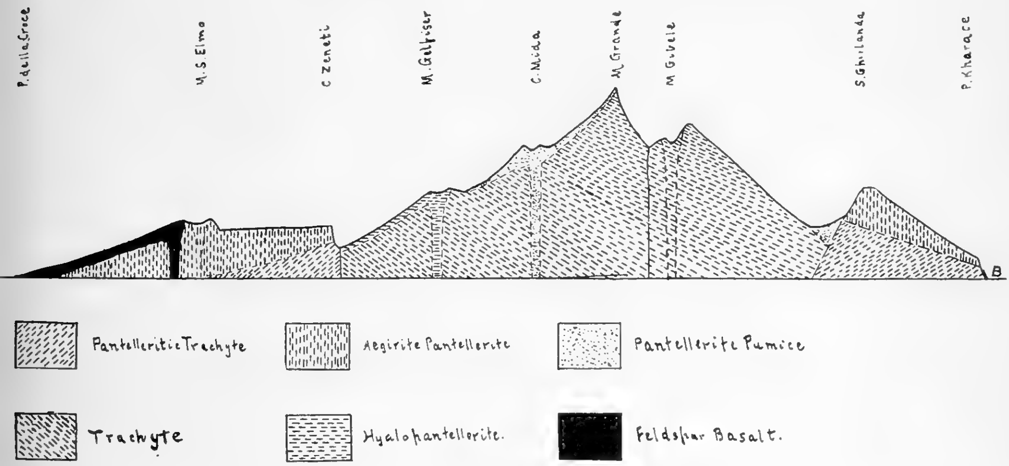

FIG. 5

of a line of fracture. The hot springs occur in various parts of the island, chiefly near the shore, while others are found at the southeast corner of the Bagno dell' Acqua. Foerstner gives two analyses, from which it appears that the waters of the lake are high in soda, with some potash, chiefly as chlorides, with less sulphates and carbonates.

To sum up, my idea of the volcanic succession may be briefly put thus:

Phase I: Building-up of a large cone, composed of flows of pantelleritic trachyte, comendite, and lastly green pantellerite. Attalora and Gadir and Monte Sant' Elmo are parasitic cones of this.

This phase was ended by an explosion, or possibly by a subsidence, blowing off the central and upper parts of the cone, forming a large caldera in the center, and leaving Serra di Ghirlanda, and Coste Zichidi, Monastero, Zeneti and Nera as a surrounding somma.

Phase II, Subphase 1: The building-up within the caldera of the Gibelé–Montagna Grande cone, with its crater probably that of Gibelé, the lavas being trachytes. Cuddia Mida was a parasitic vent, ejecting pantelleritic pumice, and the last eruptive crater of this subphase, which was concluded by the dislocation of the Montagna Grande block, which tilted up toward the south and down toward the north.

Subphase 2: The eruption of black pantellerite along the fracture line surrounding the tilted block, forming the Cuddie Randazzo, Gelfiser, Russo, and Gibilé *a* and *b*, with their flows.

Phase III: Eruption of basalts alone, formation of Cuddie Ferle, Brucciate, Foerstner Volcano (1891), etc. Fumaroles and hot springs.

These relations are shown in the accompanying sections (Figs. 4 and 5), in which the vertical scale is five times the horizontal.

LOG OF WELL OF PENNSYLVANIA SALT COMPANY DETROIT, MICH.

WILLIAM H. FRY[1]
U.S. Bureau of Soils, Washington, D.C.

This Bureau has recently prepared logs of various Michigan salt wells;[2] but unfortunately the samples from which the following log was prepared did not come in until too late to be incorporated with the other work. However, it is thought advisable to make the results complete, and consequently the log is given herewith:

Depth in Feet	
2– 52	Calcareous clay
52– 200	Limestone
200– 280	Calcareous sand
280– 400	Calcareous sand
400– 550	Limestone
550– 560	Limestone
560– 572	Limestone and gypsum
572– 620	Limestone
620– 700	Shaly limestone
700– 790	Limestone
790– 815	Salt
815– 840	Limestone
840– 920	Limestone
920– 950	Salt
950–1050	Limestone
1050–1085	Salt and limestone
1085–1165	Salt
1165–1175	Dolomitic and salty limestone
1175–1270	Salt
1270–1281	Salty limestone

[1] Scientist in Soil Laboratory Investigations, Bureau of Soils, U.S. Dept. Agric.

[2] See *Journal of Geology*, XXI, 320–22 (1913); and *Bulletin 94*, Bureau of Soils, U.S. Dept. of Agriculture.

REVIEWS

The Mining World Index of Current Literature. By GEO. E. SISLEY. Chicago: Mining World Co., 1913. Pp. 234+xxiv. $1.00.

A comprehensive list of current literature of mining, metallurgy, and allied industries for the second half of 1912. The list is arranged alphabetically by authors. For each article the title, the periodical in which it appeared, the date of issue, the approximate number of words, and the price of the article are given. The general index is supplemented by an author index and a title index. In the catalogue proper papers are grouped under the following heads: "Metals and Metal Ores," "Non-Metals," "Mines and Mining," "Mill and Milling," "Power and Machinery," "Miscellaneous." The value of such a reference work is so obvious as to require no comment.

A. D. B.

Mineralogical Notes, Series 1 and 2. By WALDEMAR T. SCHALLER. Washington, 1911, 1912. U.S. Geol. Survey Bulls. No. 490, pp. 109, figs. 14, and No. 509, pp. 115, figs. 5, pl. I.

The author includes in these two bulletins notes on crystal measurements and chemical analyses of a number of mineral species—some forty papers in all. The material is of interest chiefly to the mineralogist and crystallographer. It appears to be the beginning of a new series of papers to be issued as bulletins of the Geological Survey.

A. D. B.

Determinative Mineralogy. By J. VOLNEY LEWIS. New York: John Wiley & Sons, 1913. Pp. 151, figs. 68. $1.50.

This book follows the general plan of Brush-Penfield, with some changes in arrangement, considerable condensation, and the elimination of the rarer minerals. These changes seem to be decidedly advantageous for ordinary determinative laboratory work. The key is not so well arranged for very rapid work as Moses and Parsons; but this is more than outweighed by the greater completeness of Lewis' tables.

In the reviewer's opinion it is by far the most satisfactory determinative work that has appeared in recent years, and should quickly find its place in many laboratories.

A. D. B.

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THE

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NOVEMBER–DECEMBER, 1913

DIASTROPHISM AND THE FORMATIVE PROCESSES. IV

REJUVENATION OF THE CONTINENTS

T. C. CHAMBERLIN
University of Chicago

That extensive peneplanation and wide sea-transgression had already taken place as early as the Ordovician period will scarcely be questioned by those who have studied the relations of the Paleozoic to the Proterozoic and Archean terranes. That wide

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North America. And yet, notwithstanding the intricacy and strength of the early reliefs, about one-half of North America was not only well peneplaned as early as the Mid-Ordovician stage,

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but it was already covered by a wide, shallow sea, and there is indirect evidence that the rest of the continent had been brought to a relatively low level. While as yet studies on the peneplanation of some of the continents are little more than reconnaissances, there is sufficient evidence from such partial observations to warrant the belief that great progress toward a base-level had been made on all continents as early as the Ordovician period.

To broaden the support of these conclusions, it may be noted that the evidence of peneplanation is not confined to beveling surfaces cutting across upturned beds, or even to these combined with the wide extension of epicontinental strata. There is evidence of much cogency, though indirect and inferential, in the relative scantiness of terrigenous silts in the beds laid down near the land. Had the surface near the submerged areas remained high, the terrigenous silts must have had a nature and abundance appropriate to the drainage of high ground and would thus have testified to the fact of elevation. But some of the formations that mark the maximum sea-transgressions show a singular lack of coarse and abundant terrigenous silts. There were limestones that were certainly laid down in shallow, agitated water and yet maintained a high degree of purity, even on close approach to lands that were then emergent. This seems quite clearly to imply a low land surface from which only limited wash was derived. This inference is quite in harmony with the nature of the case, for a peneplanation that was effective enough to reduce a large fraction of the continent to a plain upon which the sea could creep forth would almost inevitably have reduced the remainder to low relief.

There is no need to dwell at length upon the processes of planation further than to recall the conception that runs through this discussion, the central feature of which is the close adjustment of a group of co-ordinate processes to the sea-surface as the controlling agency. The processes above the sea-surface embrace all those that gradually lower the land to the level of the sea at which their efficiency ceases. The processes below the sea-level embrace all those that co-operate with these in staying the terrigenous silts at the sea-border and building them into shelves just beneath the sea-surface. The mature result is a continental terrace, formed of a

girdling sea-shelf continuous with the peneplain of the land, the joint product of base-leveling on the reliefs, wave-cutting at the edge of the land, and shelf-building under the edge of the sea. All these were automatically adjusted to one another and to the sea-surface.

The slow partial filling of the sea that ran hand in hand with this gradation lifted the water-level, aided its landward progress and made room for new depositions on the surface of the growing shelf. Given sufficient time without disturbance, the process would inevitably have reduced the whole summit of the continent to a plain and even have submerged it beneath the sea-surface. The ultimate result would have been the reduction of the entire continental surface to a single terrace-top covered by an unbroken shelf-sea.

We have already noted that such a degree of progress toward complete peneplanation and sea-transgression had been made by the Mid-Ordovician stage that complete submergence must inevitably have ensued before the close of Paleozoic history, if there had not intervened some form of continental rejuvenation.

It is clear, however, that the prolonged state of quiescence requisite for complete base-leveling and submergence never was realized. The continuity of the land is attested by the terrigenous deposits that at no time were completely absent. The continuity of land life, after its early introduction, is attested by its own record and by evolutionary evidences. This testimony to the continuity of the land and of the land life would be cogent evidence of the rejuvenation of the continents if it stood alone. But it is reinforced by the record of the deformations that interrupted the course of earth history and that are yet to be sketched but may here be anticipated.

But, if these are facts of history, they can scarcely stand alone. The fact of continental rejuvenation implies suitable conditions and modes of action in the body deformed. If it is really true that the continents have been rejuvenated instead of being replaced by protrusions somewhere else, there is in this an intimation of appropriate conditions in the continents themselves. Either the continental matter was lighter than the suboceanic matter, or the attitude of continents to the basins was such as to favor a renewal of the

protrusion of the continents, or else both of these combined their good offices, as is most probable. There do not seem to be other competent alternatives.

If the rejuvenation really occurred at intervals, as implied in the statements already made, while the denudation of the continents, the loading of the borders of the basins, the loss of heat, the internal changes and other assigned agencies of deformation have been continuous, there must apparently have been *some adequate means of accumulating the constantly growing stresses* until a stress-limit was reached and yielding followed. This power of accumulation must have been *adequate* to the deformative results that followed. This forces a consideration of internal conditions.

The critical question that now arises is this:

Is the earth essentially a plastic body or at most a visco-solid, as so long held, or is it essentially an elastico-rigid body? This seems to me nearly equivalent to the question: Is the earth essentially a fluidal or quasi-fluidal body, or is it essentially a crystalline body? No one questions that it is partly the one and partly the other, but which is it dominantly in its working habit? If the main mass of the interior is fluidal or quasi-fluidal, the whole may well be viscous or plastic in its body habit and yield indefinitely and continuously to stresses that tend to deform it. Continuous loading may, in this case, be followed by continuous subsidence; continuous unloading, by continuous uprising, if hydrostatic equilibrium had been disturbed. Not so with a typical crystalline mass. The crystalline structure has for one of its essential features the definite arrangement of the molecules of each crystal in determinate positions with reference to adjacent molecules. Any stress that tends to move them from these determinate positions is resisted by an elastic force. Up to the elastic limit a strain only results, not a shear. Deformation is thus specifically limited until the elastic yield-point is reached. Beyond this the mass may be sheared, granulated, or fractured.

When crystals are intimately interlocked, as they are in typical holocrystalline rocks, the joint mass partakes of the qualities of the interlocked integers. In such a firm inter ocking of elastico-rigid units, stress gives rise to strain, but not to continuous shear, up to the yield-point of the elastic mass or of some of its integers. Beyond

this—but in the main only beyond this—shear movement or fracture movement may take place. Stresses must thus accumulate to a certain value before appreciable movement will set in. In this lies a basis for periodic movement in distinction from continuous movement, for under growing stress there is practically no movement until the yield-point is reached, when distinct and relatively free movement follows until the stress is eased.

Notwithstanding the radical difference between the behavior of a plastic and of an elastic body respectively under constantly growing stress, there are two ways in which deformative movements in bodies of the elastic type may simulate in outward aspect those of the plastic type. In an elastic crystalline body, a more or less gradual movement may take place when the interlocking crystals are so constituted that the stresses brought to bear on the whole mass are concentrated upon certain points at which the crystals press with so much special intensity and inequality upon one another that the point of solution, fusion or fracture is reached for these minute parts under these exceptional and unequal stresses. These minute parts then yield, and the dissolved, fused or granulated material readjusts itself at neighboring points of less stress. This material may or may not resolidify. By this yielding, similar intensified stresses are thrown upon other points which yield in turn. Thus a succession of yieldings of minute points is brought into play while the main mass remains more or less massively solid. It is a combination of two modes of movement—liquid, plastic, or granular movement at minute points, and massive movement for the rest. There is crystalline loss and usually a crystalline gain by transfer. The action is thus usually motion and metamorphism combined. The action is partial and distributive, in detail, and the *tout ensemble* very closely simulates a plastic movement—which indeed it is in part, but not as a whole. It is commonly interpreted as plastic, though it is not simply such. The best type is glacial motion.[1] When the temperature of a glacier is 0° C. and it is thus on the very border of liquidity, and when it is bathed in water on the very border

[1] "A Contribution to the Theory of Glacial Motion," *Decennial Publications of the University of Chicago*, 1904, pp. 193–204. See also Chamberlin and Salisbury, *Geology* I (1904), 294–306.

of solidity, as it is when melting is in progress, the change from ice to water and water to ice takes place with the utmost ease and is greatly facilitated by slight differences of stress. Glacial motion may then be almost as continuous and free from appreciable strains, ruptures and starts as the motion of a viscous body. But when the temperature is much lower and pervades the whole mass, its texture, and behavior are more rocklike, and strains, ruptures, starts, and microseismic phenomena are more pronounced. The mass is of course a crystalline rock of singular purity and the phenomena of strain, rupture, and start imminent in all cases under sufficient differential stresses. Crystalline orientation prevails at all stages.

The second case is found when the pressure on all sides is so intense that no separation of particles is possible and hence *continuity of contact* is forced, whatever may be the nature of the deformation that arises from the *differential* portion of the pressure, *which alone can give a typical deformative movement.* Such a deformation may take on the *aspect* of plastic deformation even though the minute process be one of granulation, or of progressive recrystallization, or otherwise.

These modes of pseudo-plastic movement, or, at most, partially plastic movement, qualify the distinctness between deformative movements normal to viscous or plastic bodies, on the one hand, and to rigid elastic bodies, on the other, without destroying the radical differences in their fundamental natures. The similarities in external aspect are of course a source of difficulty in interpretation. It is none the less necessary to take account of the distinctiveness of the opposed qualities. The nature of viscous or plastic bodies is favorable to continuous deformative movements so long as unequal stresses continue to arise. The nature of elastico-rigid bodies requires the delay of deformative movements until the inequalities of stress have reached the elastic limit of the aggregate or of its most stressed points. This difference gives the key to the interpretation of terrestrial deformations. It is in this difference that the phenomena of base-leveling, shelf-building, and sea-transgression, of the types we have set forth, find their elucidation. They seem to imply a crystalline elastic-rigid constitution of the earth-body.

There are of course other methods of determining the nature of the earth-body, such as the modes of the seismic vibrations that traverse the earth, the time-relations of the body-tides to the passing of the tide-producing bodies, and so forth. The testimony of these is indispensable to a full consideration of the nature of the earth-body, but we are here considering merely the bearing of the strictly geological arguments that spring from gradational phenomena.

As previously urged, a base-level of wide prevalence is practically impossible if diastrophic movements are in continuous progress, for warping and dislocation are inherently inimical to mature planation. So too in shelf-building, the range within which wave action is effective in distributing sediments, and the depth within which light is effective in photo-synthesis, are so narrow compared with the ranges through which warping and dislocation shift the crust that relatively little diastrophism would forestall the formation of great parallel sets of strata and wide continuity of shallow-water life.

This will become clearer, and certain additional considerations will be brought into view, if we follow out systematically a normal evolution under each of the two types now basally distinguished.

The systematic evolution of a continent under continuous diastrophism is most easily followed if we accept the view that the mean specific gravity of the continental masses is lower than that of the suboceanic masses and that a certain tendency to isostatic equilibrium between the two arises from this difference of specific gravity—a view strongly supported by concurrent lines of evidence. Probably all will agree to this in some degree at least, whatever limitation or qualification they may wish to impose upon it. If this be accepted, it is not material to our immediate purpose whether the diastrophism is actuated by internal changes of volume, by the transfer of matter and energy from below to the surface, by the transfer of matter from higher to lower levels on the surface, or by all combined, or by other agencies, for the trend toward isostatic equilibrium permeates all and, to the extent of its value, gives shape to their effects in accordance with mechanical laws. The portions of the crust that are already bowed outward, and are at the same time lighter than the average, are inevitably bowed upward under further stress, and the portions that are already sagged, and are at

the same time heavier than the average, are inevitably bowed downward, unless these actions are thwarted by exceptional intercurrent agencies. This inevitable tendency is made the more certain of realization by the constant unloading of the lighter outward-bowed portions and the constant loading of the heavier sagged portions. This must hold true whether the process of deformation be continuous or periodic.

Now, if the process be strictly continuous, as must be the case if a nearly perfect and constant isostatic equilibrium is maintained between the oceanic and continental segments, and between their larger parts among themselves, the evolution of the continents may be followed with logical ease. The continents must rise as they are unloaded and the ocean basins must sink as they are loaded. A secondary result must be a counter movement of the suboceanic material by virtue of which it pushes beneath the eroded continents to compensate their loss. The obviousness of this appears at once if perfect fluidity, the condition of perfect isostasy, is substituted for the existing rigidity that masks the real trend of present tendencies. A perfect adjustment would then take place promptly by vigorous movements of the kind indicated. If a viscous condition were substituted for that of free fluidity, the process would be slower but none the less inevitable. If the viscosity were high, the process would be greatly delayed but would follow the same lines. If the inequalities of specific gravity hold for the larger topographic features, the tendency will be to reproduce them, for the most protuberant portions are most eroded, in general, and suffer most from transportation. They are hence most lightened and must be most elevated in a strictly isostatic process. The continent is thus forced to reproduce itself automatically and, in theory, must continue to do so until the actuating agencies, the primitive differences in specific gravity, are removed.

This alternative cannot apparently be accepted, for the gradational phenomena seem to be decisively against it.

If we turn to the alternative view, and assume that the body of the earth is essentially crystalline, and is rigid up to the elastic limit of the most stressed points of the crystals, and that, aside from strain, the mass does not move until the elastic limit or the solution

or fusion limit of the stressed points is reached, deformation naturally becomes fundamentally periodic. As already remarked by way of qualification, a multitude of minute local periodic motions may so combine as to give the semblance of a continuous motion, but even in this case the precise mode of action and the nature of the effects differ radically from continuous fluidal or plastic flow. Normally, in an elastico-rigid earth, strains should accumulate until they attain marked intensity and should then yield either to a slow massive movement of great magnitude—as is the common case in ordinary diastrophism—or else to a sudden swift movement of less magnitude—as is the case in earthquakes. The latter type is demonstrably non-continuous. There is certainly a period of accumulating strain, with inappreciable motion, followed by quick and often catastrophic movement. Between this class of demonstrative actions and the almost continuous phases of creep, there is believed to be a graded series of cases in each of which the movement is in essence periodic though the general expression varies from nearly continuous movement to sharply periodic movement. In the latter case there may be long intervening stages of relative quiescence.

Periodic movements of all these varieties are consistent with the acceptance of a qualified doctrine of isostasy, i.e., approximate isostasy attained by periodic movement, not complete isostasy attained by continuous movement. This qualified isostasy may be nearly complete, so far as vertical balancing is concerned, just after the periodic movement has ceased. Afterward there is a gradual departure from a strict balancing while stresses are reaccumulating. This leads on to a renewed movement of adjustment and so the periodic process continues. There is in this a rhythmical approach to isostasy.

Now this seems to meet the conditions of the case. It has already been repeatedly urged that the base-leveling process cannot normally reach the stage of an advanced peneplain if continuous warping of the crust is in progress. On the contrary, the crust must hold an approximately static attitude long enough for the gradational process to accomplish the results observed. It has been further urged that there goes with the base-leveling process an

important class of marine deposits and a typical kind of life. So far then as the testimony of these highly important formations bear on the problem of continental rejuvenation, they imply that it was not a continuous steadily progressive process but that it recurred at such wide intervals as to permit great advances toward mature base-leveling as well as the evolution of shelf-seas, of parallel terranes, and of cosmopolitan faunas. All this seems in turn to imply an elastic, rigid, crystalline earth. The form of isostasy that is compatible with this has its working method in periodic approaches to complete isostasy through the successive accumulation and easement of strains in the body of the earth.

THE VOLCANOES AND ROCKS OF PANTELLERIA

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PART II

Petrography[1]

The rocks of Pantelleria have been described in modern times only by Foerstner[2] and Rosenbusch.[3] Most of the names assigned by Foerstner are not in accord with present nomenclature or the rock characters. His "phonolites" contain so much silica that no nephelite could form, they being quartz-bearing instead, and his "andesites" contain no soda-lime feldspar, the triclinic feldspar present being a soda-microcline. His "liparites" may best be considered as pantellerites—a group discovered by him, and with well-marked characters, though his synonym, "dacite-liparite," is open to the same criticism as his "andesite." His basalts are normal feldspathic ones.

Rosenbusch describes some of the rocks in detail, while others are only mentioned. He accepts Foerstner's group of pantellerites, to which he refers his "liparites." He remarks on the anomalous character of the "phonolites" and "andesites," but retains Foerstner's names, the highly siliceous composition of the former and the peralkalic character of the latter not being taken into consideration.

The following rocks, named according to the Qualitative System, occur on Pantelleria, their positions in the Quantitative System being also given. They will be described in this order.

[1] The specimens collected by me are supplemented by a set collected by Mr. F. H. Butler of London in 1891, and obtained from him in 1897.

[2] H. Foerstner, *Boll. Com. Geol. Ital.*, 1881, pp. 533–38.

[3] H. Rosenbusch, *Mikr., Phys.*, Vierte Aufl., II, No. 2 (1908), pp. 839, 851, 926, 967, 1039, 1115, 1357. A few very brief descriptions are given by G. T. Prior (*Min. Mag.*, XIII [1903], 254).

Rock Names	Subrangs
Soda trachyte	Kallerudose, I. 4. 1. 4 Nordmarkose, I. 5. 1. 4
Pantelleritic trachyte	Grorudose, II. 4. 1. 3
Comendite	Grorudose, II. 4. 1. 3
Aegirite pantellerite	Grorudose, II. 4. 1. 3
Hyalopantellerite	Varingose, II. 3. 1. 3 Grorudose, II. 4. 1. 3
Basalt	Camptonose, III. 5. 3. 4

SODA TRACHYTE, GIBELÉ TYPE (GIBELAL NORDMARKOSE)

Occurrence.—Lavas of this type, the "andesites" of Foerstner and Rosenbusch, constitute the mass of Montagna Grande and Monte Gibelé, covered in places with beds of pumice or flows of hyalopantellerite. The sheets of lava which make up the scarps of Montagna Grande are massive and often show a roughly columnar structure, while those of Monte Gibelé are, in general, less massive and compact. Along Costa Zichidi they form the uppermost flows, extending westward to the sea near Porto Scauri. Trachyte tuffs do not seem to occur.

Megascopic characters.—Lavas of this type vary from very compact forms to those which are somewhat vesicular. Strictly scoriaceous flows were not observed and even those which are vesicular show streaks of compact rock. The color is a light gray, the feel is rough and the texture highly porphyritic.

Practically the only phenocrysts visible are of alkali feldspar, which form from 25 to 30 per cent of the rock, so that the type is dopatic. These are tabular, highly cleavable, with glistening surfaces, colorless and transparent, and are 1 to 2 cm. in diameter. A few small (1–2 mm.) phenocrysts of black augite are present, but they are so few in number and so inconspicuous as to be negligible. The groundmass is a light ash gray and almost aphanitic, though the lens reveals the presence of light and fewer dark particles, and it is clearly phanerocrystalline. In megascopic habit these rocks resemble so closely some from Ischia and the Phlegrean fields as to be almost indistinguishable from them.

Microscopic characters (*Fig. 6*).—The microscopic characters of this type from Pantelleria have been described by Rosen-

busch,[1] with whose observations my own coincide in nearly all particulars.

The most abundant and largest phenocrysts are of soda-microcline, in thick tables, parallel to *b* (010), or in stout prisms elongated parallel to the vertical axis, either euhedral or subhedral, and often fragmentary. Some of these show a microperthitic structure in very fine lamellae, which resembles the lamellar twinning of the soda-lime feldspars and accounts for Foerstner's designation of "andesite." Typical microcline grating-structure is rare in my specimens, but Carlsbad twinning occurs. In many cases the feldspar phenocrysts are free from inclusions, but in others, especially from Monte Gibelé, there are inclusions of augite (which is often poikilitic and extinguishes simultaneously in isolated patches).

A few small phenocrysts of augite are present. They are mostly stout subhedral prisms, either colorless or light greenish and non-pleochroic. Aegirite-augite is either wanting or very rare, but occurs in the rocks from Costa Zichidi and its neighborhood. No phenocrysts of either hornblende or biotite are present, and small phenocrysts of olivine were only rarely seen, though Rosenbusch notes this mineral as an almost constant phenocrystic accessory. Small irregular grains of magnetite are fairly constant, but always in small amount, this type and the basalts being the only rocks of the island in which it occurs.

The typical groundmass is holocrystalline, but a little glass may be present occasionally, and some of the Gibelé lavas are quite vitrophyric. Soda-microcline makes up the greater part, either in short, small laths or anhedra, both being present in the same specimen. A flow texture is more or less well developed, though this seldom assumes a typically trachytic fabric.

The mafic[2] minerals in the groundmass are pyroxene and hornblende. The former is a colorless augite, less often greenish and aegiritic, in prisms or more abundant anhedra. No hypersthene

[1] H. Rosenbusch, *Mikr. Phys.*, II, No. 2 (1908), p. 1115; on p. 926 he speaks of them as trachytes.

[2] Equivalent to ferromagnesian; cf. Cross, Iddings, Pirsson, and Washington, *Jour. Geol.*, XX (1912), 560.

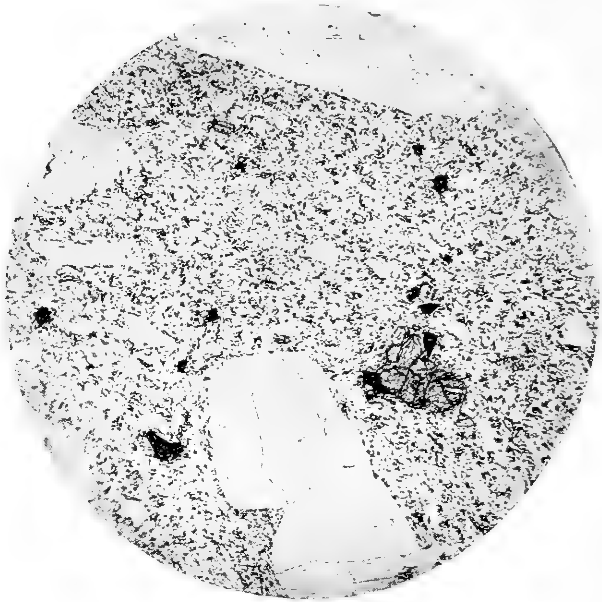

FIG. 6.—Trachyte, Montagna Grande. × 20

FIG. 7.—Pantelleritic trachyte, Costa Zeneti. × 20

could be identified by me. The hornblende is a very dark chestnut brown, intensely pleochroic, in small prisms and anhedra, which show no cleavage. It is probably cossyrite, as suggested by Rosenbusch, or possibly kaersutite, which has been found on Linosa. The latter is suggested by its pure brown color, without the reddish tinge so characteristic of cossyrite, and the nearly or quite parallel extinction of the small prisms in some specimens from Montagna Grande. The hornblende frequently surrounds and is later than some of the groundmass feldspars, while the pyroxene belongs to an earlier period of crystallization.

No magnetite is present in the groundmass of any of my specimens, but flakes of orange or blood-red hematite occur in some cases, which do not seem to be secondary. A little quartz may be detected in some cases as an interstitial residuum, but its amount is small.

Hyaline facies.—A specimen from the surface of a flow at Costa Zichidi, which is somewhat vesicular, is different from the others. In thin section are the usual feldspar phenocrysts, with rounded ones of red-brown cossyrite, a few of aegirite-augite, but none of augite. The groundmass consists largely of a pale yellowish glass, containing minute laths of feldspar. This glass is thickly crowded with peculiar dendritic growths of a deeper brown color which often assume a globular form from 0.2 to 0.5 mm. in diameter, and again larger irregular areas. Feldspar phenocrysts usually form the nucleus of these. They are made up of small grains seldom more than 0.01 mm. in diameter, either equant or elongated.

Toward the center of the spherulites the grains are thickly crowded, but they separate at the borders, which consist of small, irregular, radially divergent tongues and processes. The grains are light yellow in color with rather high birefringence, the areas showing a faint aggregate double refraction. Their extremely small size makes optical determination difficult, but they are probably an aegiritic augite.

Chemical composition.—Analyses were made of a specimen from a massive flow near the base of the southwest scarp of Montagna Grande, below Rione Miliac, of one from the crater of Monte

Gibelé obtained from Mr. Butler, and of one from the top of Costa Zichidi. Two by Foerstner are also given, one of the Montagna Grande rock and one of a flow at Porto Scauri.

ANALYSES OF TRACHYTE, GIBELE TYPE

(GIBELAL NORDMARKOSE)

	A	B	C	D	E	A*a*	B*a*	C*a*
SiO_2	63.43	63.30	65.27	61.47	61.43	1.057	1.055	1.088
Al_2O_3	16.31	16.38	13.50	18.09	17.51	.160	.161	.132
Fe_2O_3	2.04	2.54	4.40	5.14	5.11	.013	.016	.028
FeO	3.14	2.36	2.52	3.06	2.30	.043	.033	.035
MgO	0.78	0.84	0.55	1.32	0.54	.020	.021	.014
CaO	1.70	1.62	0.85	3.00	2.45	.030	.029	.015
Na_2O	6.71	6.36	5.19	5.85	6.22	.108	.103	.084
K_2O	4.31	4.41	4.21	2.83	3.95	.046	.047	.045
H_2O+	0.18	0.83	1.98	n.d.	n.d.	....	....	....
H_2O-	0.26	0.10	0.14	n.d.	n.d.	....	....	....
TiO_2	1.19	0.71	1.09	n.d.	n.d.	.015	.009	.014
ZrO_2	0.06	....	....	....	....	....	....	....
P_2O_5	0.20	0.30	0.17	n.d.	n.d.	.001	.002	.001
SO_3	0.05	....	....	....	....	....	....	....
MnO	0.04	n.d.	0.27	n.d.	n.d.	.001	....	.001
BaO	0.05	....	....	....	....	....	....	....
	100.45	99.75	100.14	100.76	99.51	....	....	....

A. Below Rione Miliac, Montagna Grande. H. S. Washington, analyst.
B. Crater of Monte Gibelé. H. S. Washington, analyst.
C. Costa Zichidi. H. S. Washington, analyst.
D. Montagna Grande. H. Foerstner, analyst. *Zeits. Kryst.*, VIII (1884), 155.
E. Porto Scauri. H. Foerstner, analyst. *Zeits. Kryst.*, VIII (1884), 164.
A*a*, B*a*, C*a*, mol numbers[1] of A, B, C, respectively.

The first two analyses are typical ones of distinctly sodic trachytes, slightly high in silica and with very high TiO_2, considering the salic characters of the rocks. They are remarkably alike and indicate a general uniformity in the flows of the Gibelé volcanoes, since A, coming from the foot of the Miliac scarp, must be considerably older than that from the Gibelé crater. The analysis of the Zichidi rock C resembles them in general features, but is higher in silica and ferric oxide and lower in alumina, magnesia, lime, and soda. Except for the lower soda it shows affinities toward the pantelleritic trachytes.

Foerstner's analyses cannot be regarded as very satisfactory, partly because of the non-determination of water, titanium, and

[1] This term is used instead of molecular ratios, following Wright and Van Orstrand (*Jour. Wash. Acad. Sci.*, III [1913], 233).

phosphoric oxides, and partly because of certain features which will be discussed later. They indicate, however, that the silica is probably lower in some of these trachytes than in my analyzed specimens.

The norms of A, B and C are given below:

	A	B	C
Q	3.90	5.58	17.10
Or	25.58	26.13	25.02
Ab	56.59	53.97	44.01
An	1.67	3.06	0.83
Di	4.83	2.48	1.94
Hy	1.59	1.96	0.50
Mt	3.02	3.71	5.57
Hm	....	....	0.64
Il	2.28	1.37	2.13
Ap	0.34	0.67	0.34
	99.80	98.83	98.08
Rest	0.64	0.93	2.12
	100.44	99.76	100.20

The magmatic symbol of A is I(II).5.1.4, that of B is I(II).″5.1″.″4, and that of C is I(II).4.1.(3)4, using the notation recently proposed[1] to indicate the exact position of a rock magma in each division of the Quantitative System. The first two are in nordmarkose, in the persalane class but transitional toward dosalane, and hence are strictly to be called umptekose-nordmarkose, B not being as centrally placed in the other divisions as A. The excess of silica is so small as to be negligible. The Zichidi rock also falls in the same place as regards the class, but is in order 4, and its dosodic subrang is transitional toward the sodipotassic one, so that it is a liparose-kallerudose. Here the amount of normative quartz is notable, indicating its tendency toward the pantelleritic trachytes. It is to be noted that these trachytes (and the basalts) are the only Pantelleria rocks which show normative anorthite, so that, in spite of the presence of aegirite-augite, no acmite appears in the norm.

[1] Cross, Iddings, Pirsson, and Washington, *Jour. Geol.*, XX (1912), 554. I use the sign″ to indicate that the position is intermediate but not transitional; that is, between the central portion and the transitional border.

Mode.—Owing to the fine grain and complex texture of the groundmass, an exact estimate of the mode by microscopic measurement is impossible. When the norm is compared with the thin sections the amount of mafic minerals—pyroxene and hornblende—present is seen to be much larger than that of the normative pyroxene, while but a very small proportion of the normative ores is present in the mode. The mode is, therefore, somewhat abnormative, and it is clear that readjustments of the norm to estimate the mode must consist chiefly in combining the normative ores and pyroxenes with some silica and albite. These readjustments cannot be made with certainty, as two pyroxenes and a hornblende are present and their composition is unknown. But the amounts of these are small and, taking the thin sections into consideration, the following will represent fairly well the relative amounts of minerals present in my analyzed specimens from Montagna Grande A and Zichidi B.

	A	B
Quartz	3	13
Soda-microcline	83	70
Aegirite-augite	7	9
Hornblende	5	6
Magnetite	2	2
	100	100

These rocks are evidently slightly quartzose soda-trachytes, that of Zichidi containing so much quartz as to be transitional to the rhyolites. As this, however, is confined to the groundmass and is not at all prominent even there, it had best be classed with the trachytes. Their sodic character is chiefly evident in the feldspars, the augite is only slightly aegiritic, and the amount of soda-amphibole (cossyrite) very small, in these two latter respects differing from the next type.

Such alkali-trachytes have been called by Rosenbusch augite trachytes of the Ponza type. These of Pantelleria differ widely from the true Ponza trachytes, which Rosenbusch has described and specimens of which I have studied, in the total absence of biotite, either as such or as augite-magnetite aggregates represent-

ing original biotite crystals. The Ponza trachytes also differ chemically, especially in a higher potash content, judging from the only analyses of them which appear to have been made.[1] As occurrences of these sodic trachytes are becoming rather common, it might be well to call the true Ponza type, with biotite, *ponzite*, and those of the Pantelleria type, *gibelite*.

PANTELLERITIC TRACHYTE, ZENETI TYPE (ZENETAL GRORUDOSE)

Occurrence.—Rocks of this type, which are the "phonolites" of Foerstner, form flows seen in the lower portions of the internal scarps of the large, first-period caldera, notably at Costa Zeneti and Costa Zichidi. The type also occurs near the base of the more precipitous portions of the coast line, as near Punta Pozzolana and Cala Cinque Denti on the north, the coast from Punta Tracino to Punta Kharace on the east, and various stretches on the south and southwest. These coastal occurrences presumably are extensions of flows, the more central portions of which form the bases of the internal scarps, and rocks of this type may be regarded as the earliest known outpourings of the Pantelleria volcano.

Megascopic characters.—Rocks of this type are of a rather dark-gray color, and are usually compact, but slightly vesicular forms occur. The only phenocrysts visible are very small (1–2 mm.), glistening, white tables of feldspar, which are not conspicuous and make up less than 5 per cent of the mass. Here and there are equally small, black grains of augite, but the amount of these is quite negligible. The slightly brownish, dark-gray groundmass is dense and aphanitic, and in some specimens shows evidence of vitreous texture.

Microscopic characters (Fig. 7).—A brief description of the microscopic characters of some of these rocks has been given by Rosenbusch,[2] which coincides with my own observations and the few statements of Foerstner.[3]

The most prominent phenocrysts are soda-orthoclase, though they are not large or abundant. They are euhedral and tabular

[1] C. Doelter, *Akad. Wiss. Wien*, XXVI, 1875, pp. 148, 151.

[2] H. Rosenbusch, *Mrik. Phys.*, II, No. 2 (1908), pp. 839, 967, 1115.

[3] H. Foerstner, *Boll. Com. Geol. Ital.*, 1881, p. 534.

parallel to *b* (010), often showing Carlsbad twinning. A few small, euhedral, stout prisms of a rather bright-green, pleochroic aegirite-augite are also present, but no cossyrite phenocrysts were observed in my specimens or noted by Rosenbusch.

The groundmass is typically holocrystalline, and consists of numerous small prisms and anhedra of aegirite and hornblende in a colorless base of quartz and alkali-feldspar. Most of the aegirite is in the form of euhedral to subhedral prisms, never more than 0.2 mm. long and about 0.05 mm. thick, and usually much smaller, while small anhedral grains are also common. Its color is light green, extremely pale in the smaller individuals, and it is distinctly pleochroic, especially in the larger and more deeply colored individuals: $\mathfrak{a}$ grass-green, $\mathfrak{b}$ and $\mathfrak{c}$ lighter yellowish green. In the smaller and paler crystals the pleochroism is not well-marked. The deeper colored individuals show extinction angles $c \wedge \mathfrak{a}$ up to 24°, so that they are to be regarded as aegirite-augite, while in the small prisms the angle is much less and they may be considered to be almost or quite pure aegirite, though extremely light in color.

The hornblendes are by no means as well formed as the pyroxenes, and while many of them show a prismatic development, definite crystal faces are lacking, and many individuals are small, anhedral grains. Cleavage is not developed. The color is a deep chestnut brown and the mineral is highly pleochroic, an almost opaque brown and a light hair-brown. Between crossed nicols this hornblende often shows a peculiar, brilliant, copper color. This hornblende is presumably the cossyrite which forms phenocrysts in other Pantellerian lavas, as is suggested by Rosenbusch, though the pleochroism is somewhat different. A few small, anhedral grains of grayish blue, apparently arfvedsonitic hornblende, were seen in some sections, but their presence is exceptional.

The pyroxenes and hornblende are present in about equal amount, but there seems to be usually more of the former. They are often clustered in somewhat curved, narrow groups, the "dendrites" of Foerstner, which produce what might be called a wreath texture. The colorless base, seen between crossed nicols and

rather high powers, resolves itself into an aggregate of very small alkali-feldspar individuals, which vary in form from euhedral prisms to anhedral grains, imbedded in an interstitial cement of quartz. This last is often micropoikilitically developed,[1] areas with uniform extinction inclosing the small feldspars. This quartz is doubtless the mineral called nephelite, unequivocally by Foerstner and doubtfully by Rosenbusch, but which the large

ANALYSES OF PANTELLERITIC TRACHYTE

(ZENETAL GRORUDOSE)

	A	B	A*a*	B*b*
SiO_2	64.54	63.77	1.076	1.063
Al_2O_3	11.49	11.18	.113	.110
Fe_2O_3	5.14	5.02	.032	.031
FeO	2.99	2.58	.042	.036
MgO	0.89	0.51	.022	.013
CaO	0.64	1.37	.012	.025
Na_2O	5.46	5.55	.089	.090
K_2O	4.66	4.35	.050	.047
H_2O+	1.11	2.72	....	....
H_2O-	2.12	1.28	....	....
TiO_2	0.90	0.94	.011	.012
ZrO_2	0.08	....	....	....
P_2O_5	0.16	0.14	.001	.001
‘ O_3	0.17	....	....	....
MnO	0.13	0.26	.002	....
	100.48	99.67	....	....

A. Base of Costa Zeneti. H. S. Washington, analyst.
B. Base of Punta Pozzolana. H. S. Washington, analyst.
A*a*. Mol number of A. B*a*. Mol number of B.

amount of free silica present in the norm shows cannot exist in the rock. Biotite is not present and no grains of magnetite were seen.

Hyaline facies.—A specimen of a hyaline facies of this type merits brief description. It forms a flow at sea-level at Punta Pozzolana.[2] It is compact, very dark grey, and with very few feldspar phenocrysts visible. In thin section these feldspars show no feature worthy of special note, and phenocrysts of aegirite-augite and hornblende are extremely rare. The groundmass is

[1] Cf. P. Geijer, *G. För. Stockh. Förh.*, XXXIV (1913), 51.

[2] At Punta Pozzolana I found no rock corresponding to the "trachydolerite" mentioned by Prior from this locality.

dohyaline and hyalopilitic, composed of a colorless or slightly brownish glass thickly felted with minute, slender, prismatic microlites of an almost colorless mineral, which is most probably an aegiritic pyroxene. There are also some minute laths of alkali feldspar, but not a trace of hornblende could be detected in the groundmass.

Chemical composition.—Two analyses were made of this type, and are given in the annexed table.

The rocks are distinctly higher in silica and ferric oxide and lower in alumina and soda than the preceding type, lime being lower in the main occurrences, and ferrous oxide, magnesia, potash, and titanium about the same. Foerstner (p. 534) gives a partial analysis of a Zeneti "phonolite"; $SiO_2=67.8$, $Na_2O=6.0$, $K_2O=3.8$. The high silica here is probably approximately correct, and is significant.

	A	B
Q	15.12	14.34
Or	27.80	26.13
Ab	33.01	33.01
Ac	11.55	12.47
Di	1.76	5.20
Hy	3.38	1.42
Mt	1.62	0.93
Il	1.67	1.82
Ap	0.34	0.34
	97.25	95.76
Rest	3.48	4.00
	100.73	99.76

The two rocks fall well within the subrang grorudose, II.4.1.3, though that of Punta Pozzolana is intermediate toward pantellerose, II.4.1.4. The chief interest of these norms lies in the fact that, in spite of the dominance of soda over potash shown in the analysis, the rocks are sodipotassic in their classificatory position. This is due to the small amount of alumina which necessitates the formation of femic acmite. The amount of alumina is too high, or that of soda too low, to permit of the formation of normative sodium metasilicate, which we shall meet with in the pantellerites.

Mode.—The groundmass is too fine grained, and the texture too confused, to permit of satisfactory measurements by Rosiwal's method of the relative amounts of the constituent minerals, but a recalculation from the norm, taking the thin sections into consideration, yields the following mode for the Zeneti trachyte:

Quartz	15
Soda-microcline	63
Aegirite-augite	12
Hornblende	10
	100

These trachytes are in many ways intermediate between the Gibelé trachytes and the pantellerites, so that the name of pantelleritic trachyte is applicable to them.

COMENDITE, NERA TYPE (NERAL GRORUDOSE)

Occurrence.—Flows of this rock—the "white liparite" of Foerstner—form sheets above those of the preceding type. They are met with at various points along the inner scarp of the caldera wall, notably at Cuddia Nera, where two superposed flows are seen, the upper being platy in structure and the lower distinctly columnar and the rather narrow columns often curved. They are capped by a thin sheet of the green pantellerite, next to be described. The type also occurs in the scarp of Costa Zichidi, on the west side of the Val di Monastero, and on the southeast side of the Valle Silhoumen, according to Forestner, though I did not see it here. Foerstner mentions it at the so-called Polveriera, the ancient citadel of Cossyra, southeast of the town, but probably terracing for vineyards has since covered the exposure as I observed here only basalts from the Sant' Elmo flow. Along the steep parts of the coast flows of this rock are seen, occurrences being at Punta Pozzolana, Cala Cinque Denti, and Cala Porticello. At the first of these the rock is rather tuffaceous, is covered by a yellowish pantelleritic tuff, and overlies a flow and scoria bed of black and green pantellerite, while at the sea-level is the vitrophyric zenetal grorudose described above. This type is briefly described by Rosenbusch.[1]

[1] H. Rosenbusch, *op. cit.*, p. 839.

Megascopic.—The rocks are compact and generally a very light gray, almost white, though a flow at Cuddia Nera is light pinkish through weathering; small phenocrysts of feldspar are numerous, with fewer of black hornblende and augite. The groundmass is very fine grained, somewhat dull, and phanerocrystalline.

Microscopic.—The largest phenocrysts are of soda-orthoclase, which are tabular parallel to *b* (010), and are like those already described. More interesting are those of hornblende which form not more than about 2 per cent of the rock. These are euhedral to subhedral, slender prisms, about 0.5 mm. long by 0.2 mm. thick. They have the faces *m* (110) and *b* (010) well developed, but no terminal planes. The prismatic cleavage is good. When these phenocrysts occur in the groundmass they are almost invariably surrounded by a narrow border of finely granular hornblende of somewhat lighter color, which is absent from the few included in feldspar phenocrysts.

The color of the hornblende is a rather dark chestnut brown, without the tinge of red which is so characteristic of the cossyrite of the various types of pantellerites. The pleochroism is very strong; $\mathfrak{c}$ and $\mathfrak{b}$ dark brown, or almost black, $\mathfrak{a}$ light yellow brown. It was difficult to determine the extinction angle accurately owing to the intense absorption, but values of $\mathfrak{c} \wedge c$ up to 20° were observed. Though the pleochroism differs from the normal cossyrite, the other characters, as well as the chemical composition deduced from the norm, show that this hornblende is a cossyrite and not a kaersutite which it somewhat resembles.

A few subhedral phenocrysts of a bright-green, slightly pleochroic aegirite-augite are present, and in a few sections rare anhedral olivine phenocrysts.

The groundmass is holocrystalline and is mostly composed of alkali-feldspar and quartz. The former is usually in the form of minute tables, giving rise to lath-shaped sections, though some anhedral grains occur. The quartz appears as small patches, about 0.1 to 0.2 mm. in diameter, usually irregular in outline but sometimes roughly rounded, which include feldspar grains microkoikilitically. Scattered abundantly through this quartz-feldspar

base are very small crystals of green aegirite-augite and the pleochroic brown hornblende, the latter being more abundant than the former. Both of these mafic minerals form highly irregular shreds and anhedra and are seldom if ever prismatically developed, nor do they occur in the wreathlike aggregates so characteristic of the preceding type. No magnetite is to be seen in any of the specimens nor did I see the biotite mentioned by Rosenbusch.

Chemical composition.—An analysis was made of the comendite which forms the lowest, columnar flow at Cuddia Nera, this being the freshest and that which best shows the brown hornblende. An analysis of a "liparite" from Cala Porticello by Foerstner is also given, but it is very doubtful if it is of the same type as it differs much in chemical composition and he gives no description.

ANALYSES OF COMENDITE, NERA TYPE

(NERAL GRORUDOSE)

	A	B	A*a*
SiO_2	72.21	67.18	1.204
Al_2O_3	9.72	14.18	.096
Fe_2O_3	3.26	4.00	.020
FeO	1.07	2.48	.015
MgO	0.29	0.34	.007
CaO	0.82	2.78	.014
Na_2O	4.42	5.89	.071
K_2O	4.98	4.01	.053
H_2O+	1.96	n.d.	.....
H_2O-	0.24	n.d.	.....
TiO_2	0.62	n.d.	.008
P_2O_5	0.10	n.d.	.001
MnO	0.05	n.d.	.001
	99.74	100.86	.....

A. Lowest flow, Cuddia Nera. H. S. Washington, analyst.
B. "Liparite," Cala Porticello. H. Foerstner, analyst. *Zeits. Kryst.*, VIII (1884), 133.
A*a*. Mol number of A.

This type differs from those described previously in the high silica, which is the highest found by me in any rock of the island. The predominance of ferric over ferrous oxide may be noted, and the small amounts of magnesia and lime. This rock is also the only one analyzed by me which shows a greater percentage of potash than of soda, though molecularly the latter is present in greater quantity. Foerstner's partial analysis[1] is of interest in

[1] *Boll. Com. Geol. Ital.*, 1881, p. 535.

this connection: $SiO_2=73.1$, $Na_2O=2.5$, $K_2O=5.0$. This rock from the Polveriera shows about the same amounts of silica and potash as that from the Cuddia Nera, but soda is somewhat lower, though in both the percentage of potash is greater than that of soda, and molecularly they are present in about equal amount. The distinctly high potash is noted by Foerstner as a character of the rock type.

Norm.—The norm of the Cuddia Nera rock is as follows:

	Norm
Q	31.14
Or	29.47
Ab	22.01
Ac	9.24
Ns	1.10
Di	2.57
Hy	0.46
Il	1.22
Ap	0.34
	97.55
Rest	2.24
	99.74

The type falls within the dosalane class but is transitional to persalane, and is nearly on the border of order 3. The rang is decisively peralkalic, no salic lime being present, since acmite exists in the norm, and the subrang is also clearly sodipotassic. It is therefore in (I)II, (3)4.1.3, so that the type should be called a varingose-grorudose. It will be seen that acmite constitutes the greater part of the femic minerals, and the presence of sodium metasilicate in small amount is to be noted as this is characteristic of the pantellerites, being correlated in the mode with the presence of cossyrite.

Mode.—Through the presence of the hornblende the mode is somewhat abnormative. From recalculation of the norm and study of the thin sections it may be expressed approximately as follows, the cossyrite being assumed to have the composition of that analyzed by Dittrich:[1]

[1] J. Soellner, *Zeits. Kryst.*, XLVI (1909), 540.

Quartz	30
Soda-microcline	51
Cossyrite	12
Aegirite-augite	7
	100

Though the type very closely resembles the pantellerites, yet it seems advisable to follow the suggestion of Rosenbusch and call these rocks comendites, partly because of the very high silica, partly because of the high potash, and partly because of the megascopic characters and the microscopic texture of the groundmass.

AEGIRITE PANTELLERITE, SANTELMO TYPE (SANTELMAL GRORUDOSE)

Occurrence.—Lavas of this type (the "crystalline pantellerite" of Foerstner) are abundant on the island. In the north it forms flows from Monte Sant' Elmo, an area to the south of Monte Gelkhamar, and a somewhat more extensive one from near Cuddia Bonsulton northeasterly to Costa Zeneti and Cuddia Nera (forming the upper part of these), Rione Khadingia, and beyond to the coast near Punte Pozzolana and Karuscia. In the south and southeast it constitutes the mass of Cuddia Attalora and the slopes from Cuddie dietro Isola and Serra Ghirlanda to the sea. As noted above the flows of this pantellerite were the last from the early volcano, before the great caldera-forming eruption. These lavas are often accompanied by yellow tuffs. Flows of this type are generally pahoehoe, and in places the lava is made up of mingled streaks of this and the succeeding type.

Megascopic characters.—These lavas are often platy, generally compact, but again somewhat vesicular. The type is distinctly but finely porphyritic. The aphanitic, dull, and apparently cryptocrystalline groundmass is of a light yellowish-green color, which varies somewhat in different specimens. Through this are sprinkled many small (1–3 mm.), glistening, white feldspar phenocrysts, and few smaller stout prisms of black pyroxene and hornblende. Some of these are also to be seen in the crevices and vesicles, with occasional small tables of tridymite.

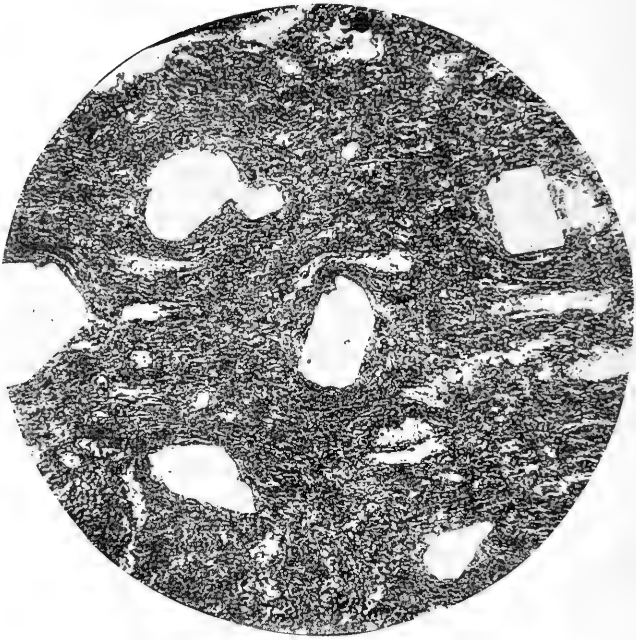

FIG. 8.—Aegirite pantellerite, Costa Zeneti. × 20

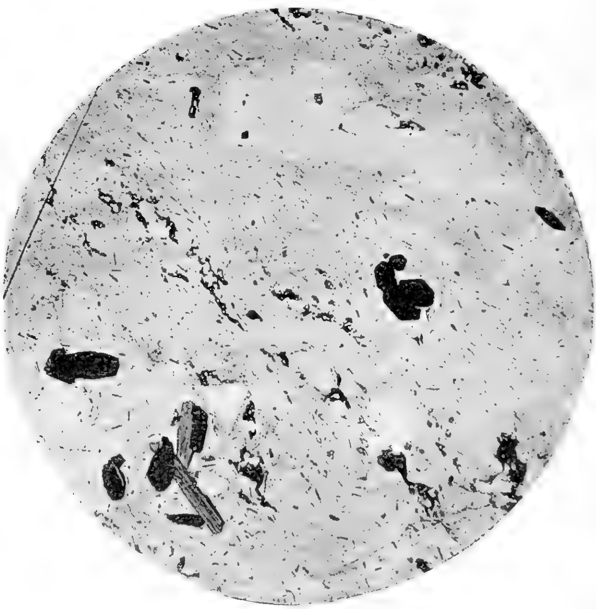

FIG. 9.—Hyalo pantellerite, Khagiar. × 20

Microscopic characters (*Fig. 8*).—The pantellerites of Pantelleria have been described in great detail by Rosenbusch,[1] who devotes especial attention to this type. Except for some minor details my observations fully bear out his descriptions.

The soda-microcline phenocrysts are not numerous in the sections. In general they are thick, tabular parallel to *b* (010), and euhedral, but are often fragmentary. They show no microcline or perthite structures and no albite twinning lamellae, but Carlsbad twins are frequent. Inclusions are rare.

In most of the specimens cossyrite phenocrysts are fairly common, while in others they are wholly wanting. They are stoutly prismatic and vary from 0.2 to 0.4 mm. in length. Originally euhedral, most of them show rounded outlines, especially at the terminations, and some are thus reduced to ovoidal forms. This is probably due to resolution by the magma, as suggested by Rosenbusch. Their color is a very deep reddish brown, with internal pleochroism; $\mathfrak{c}$ brownish black, $\mathfrak{b}$ deep chestnut brown, $\mathfrak{a}$ red brown. A few small phenocrysts of a pleochroic, grass-green aegirite-augite are present. Magnetite grains are wholly absent, but there are a few zircons. I could find none of the olivine or apatite mentioned by Rosenbusch.

This rock type has a very peculiar and highly characteristic groundmass. Under low powers it is light, yellowish white and almost opaque through the abundance of patches and streaks of a dustlike substance, which commonly show a well-developed flow texture. This invariably occupies most of the section, and in the narrow interstices is a colorless substance with feeble, diffuse birefringence.

Under high powers the opaque substance is resolved into a felt of extremely minute, transparent, nearly colorless, prismatic microlites. These must be considered to be aegirite (as suggested by Rosenbusch), though their extreme tenuity renders determination of their optical characters very difficult. It is, of course, to the presence of this aegirite felt that the greenish color of the rock is due. No cossyrite or other hornblende was observed as a groundmass constituent. The colorless base is now seen to be generally holocrystalline, and formed of an intimate mixture of very minute

[1] H. Rosenbusch, *op. cit.*, pp. 852–54.

grains of feldspar and quartz, though colorless glass is present in small amount in some sections.

Pantellerite pumice.—With this type of pantellerite may be briefly described a pumice which covers a considerable area near the center of the island, about the summit of Montagna Grande and Cuddia Mida, between Monte Gibelé and Serra Ghirlanda, and in isolated patches elsewhere. It is whitish or cream colored, becoming a brownish yellow on wetting; highly vesicular, floating easily on water. Equant phenocrysts of alkali feldspar (2–5 mm.) are rather abundant, but none of mafic minerals. A flow texture is usually well developed.

In thin section this pumice is seen to be perhyaline. A few of the feldspar phenocrysts, and still fewer and smaller ones of aegirite-augite are present. The glass base is clear and colorless, carrying only extremely small amounts of "dust" and very rare microlites of feldspar and pyroxene. No hornblende is present.

Chemical composition.—Two analyses of this type of pantellerite, and one of the pumice were made. With them are given two by Foerstner and one by Abich of pumice.

These are all consistently higher in silica and ferric oxide, and lower in alumina, lime, and magnesia, than the trachytes described previously. The only difference of note between my two analyses of the type is the alumina, the higher figure in B being partly compensated for by the slightly higher iron oxides of A. Otherwise they are almost identical. It will be observed that TiO_2 is high for such silicic rocks. Attention must be called here to the relation of the iron oxides, the percentage of Fe_2O_3 being much higher than that of FeO in both. The analysis of the pumice is closely like the others, though lower in silica, and the proportion of ferric oxide is greater. It is chiefly on this account and because of the colorless glass that it is placed with the Santelmal type. The analyses of Foerstner are unsatisfactory in their incompleteness, and also seem to suffer from the usual systematic errors. It will, however, be observed that his iron oxides, though higher than mine, show much more Fe_2O_3 than FeO. While the analysis of Abich is, of course, unsatisfactory according to modern standards, yet, considering its date, it is very creditable, the alkalies alone being improbable.

ANALYSES OF AEGIRITE PANTELLERITE

(SANTELMAL GRORUDOSE)

	A	B	C	D	E	F	Aa	Ba	Ca
SiO_2	70.14	69.79	67.32	70.30	67.48	68.11	1.169	1.163	1.122
Al_2O_3	8.61	11.91	9.55	6.32	9.70	8.21	.084	.117	.094
Fe_2O_3	6.01	5.35	6.73	9.23	7.42	8.23	.038	.034	.042
FeO	2.73	1.43	0.81	1.40	2.21	....	.038	.020	.011
MgO	0.20	0.25	0.20	0.89	0.77	0.37	.005	.006	.005
CaO	0.45	0.25	0.20	0.84	1.45	0.14	.088	.004	.004
Na_2O	5.44	5.66	5.71	7.70	7.21	8.32	.088	.091	.092
K_2O	4.20	4.59	4.48	2.50	2.94	1.60	.045	.049	.048
H_2O+	0.35	0.17	3.15	0.82	0.96	1.73	....	....	....
H_2O-	0.17	0.04	0.49	n.d.	n.d.	....	....	....	....
TiO_2	0.86	0.89	0.59	n.d.	n.d.	1.23	.011	.011	.007
ZrO_2	0.14	....	....	....	....	....	....	....	....
P_2O_5	0.12	0.13	0.08	n.d.	n.d.	n.d.	.001	.001	.001
SO_3	0.06	....	....	....	....	....	....	....	....
MnO	0.38	0.20	0.24	n.d.	n.d.	Cl= 0.70	.005	.003	.003
BaO	none	....	....	....	....	CH_4 = 0.66	....	....	....
	99.86	100.66	99.55	100.00	100.14	99.20	....	....	....

A. Monte Sant' Elmo. H. S. Washington, analyst.
B. Costa Zeneti. H. S. Washington, analyst.
C. Pumice. Rione Buccarame. H. S. Washington, analyst.
D. Khartibugal. H. Foerstner, analyst. *Zeits. Kryst.*, VIII (1884–), 173.
E. Monte Sant' Elmo. H. Foerstner, analyst. *Zeits. Kryst.*, VIII (1884–), 186.
F. Pumice of Pantelleria. H. Abich, *Vulk. Ersch.*, 1841, Taf. III.
Aa. Mol numbers of A. *Ba*. Mol numbers of B. *Ca*. Mol numbers of C.

The norms of the first three rocks are as follows:

	A	B	C
Q	27.60	21.78	22.44
Or	25.02	27.24	26.69
Ab	20.44	35.63	24.10
Ac	17.56	10.63	19.40
Ns	1.34	....	0.49
Di	1.21	....	....
Hy	4.10	0.60	1.03
Mt	....	2.09	....
Il	1.67	1.67	1.42
Hm	....	0.32	....
Ap	0.34	0.34	0.34
	99.28	100.30	95.91
Rest	0.72	0.21	3.64
	100.00	100.51	99.55

The Sant' Elmo pantellerite, therefore, falls in varingose, II.3(4).1.3, owing to the large excess of silica, but transitional to

grorudose, while the other two fall well within grorudose, II.4.1.3, B being intermediate toward liparose and pantellerose. Acmite predominates strongly among the femic minerals, and the amount of sodium metasilicate is very small or nothing, in which respect this type of pantellerite differs from that next to be described.

Mode.—Owing to the fineness of the grain the mode cannot be determined by optical means but can be recalculated from the norm, the same assumption being made as to the cossyrite as before.

A		B	
Quartz	28	Quartz	20
Or_5Ab_4	45	Or_4Ab_5	63
Aegirite	17	Aegirite-augite	14
Cossyrite	10	Cossyrite	3

This type, being holocrystalline, may be regarded as typical pantellerite, the cenotypal equivalent of Brögger's grorudite, the analyses of which are closely similar.

HYALO-PANTELLERITE, KHAGIAR TYPE (KHAGIARAL VARINGOSE AND GRORUDOSE)

Occurrence.—This type is, in general, later than the preceding, belonging to the last period of the second phase after the tilting of the Montagna Grande block and before the eruption of basalts. In certain localities, as at Sant' Elmo, Cuddia Nera, and, in the south of the island, flows of the Santelmal type show streaks and patches of this glassy black type. The cones and flows of this type are found around the tilted Montagna Grande block, at Cuddie Randazzo and Gelfiser, with their respective great flows, at the north, Gelkhamar and Sciuvechi at the northwest, the two small Monti Gibile to the west, Fosso del Russo and the lavas of Rione Benimingallo to the south, and those of Rioni Mueggine and Khamma to the east. These lava flows are of the *aa* type, the blocks being generally angular.

Megascopic characters.—The specimens from most of the occurrences are very uniform. They are black, highly vitreous rocks, composed of a pure black, generally lustrous, glass groundmass, which in some specimens is locally slightly iridescent due to incipient alteration. In the specimen from Cantina Ziton the glassy groundmass is dull and somewhat waxy in luster. This

glass is very thickly sprinkled with small (1–3 mm.), rectangular, nearly equant phenocrysts of white glistening feldspar, which do not show any flow arrangement. They are in some cases so abundant as to be present in almost as great amount as the glass, but typically the rock is dopatic. A few perpatic forms were seen—black obsidians with very rare and small feldspar phenocrysts. These pure obsidians do not seem to form flows, but occur as blocks in the yellow pantelleritic tuffs. In all the specimens examined by me this black glass is brownish in thin edges, and I saw none of the green glass noted by Rosenbusch and Foerstner.

Microscopic characters[1] (*Fig. 9*).—The numerous soda microcline phenocrysts are mostly euhedral, in stout prisms parallel to *c* or tables parallel to *b* (010), but a few are rounded as by magmatic corrosion and some are fragmentary. They are usually quite free from inclusions, but a few contain minute crystals of aegirite-augite or cossyrite. Phenocrysts of two kinds of pyroxene are present, both in very small amount. One is an almost colorless or very pale greenish-gray diopside; the other a bright grass-green, distinctly pleochroic aegirite-augite. Both occur as stout prisms, but subhedral with rounded edges, and the former is likely to be much corroded. The cossyrite phenocrysts are more abundant than those of pyroxene and resemble those of the preceding type. No arfvedsonite was seen and lime-soda feldspars and magnetite grains are wholly absent. Olivine is also wholly wanting, except in a specimen from Cantina Ziton, from a flow south of, and apparently from, Fosso del Russo. Olivine phenocrysts (about 2 per cent) occur in this in small euhedral or subhedral, slightly corroded crystals, carrying a few magnetite inclusions. No cossyrite occurs in this rock.

The groundmass is highly vitreous, the glass being brownish, never greenish in my specimens. In most specimens this glassy groundmass is dohyaline, small prisms of alkali-feldspar, with fewer of cossyrite and augite, being abundant. A flow texture is always well marked, shown by the fluidal arrangement of the microlites, as well as by streaks of more or less crystalline groundmass, some of which are almost holocrystalline and correspond to the groundmass of the Santelmal type.

[1] Rosenbusch describes this type with the preceding (*op. cit.*, p. 852).

The specimen from Cantina Ziton has a perhyaline groundmass —an almost colorless glass, slightly mottled with "dust" but free from microlites, spherulitic through the presence of yellow-brown cumulites, which are almost opaque and without action on polarized light. These are sometimes isolated and globular, and elsewhere in streaks with marked flow texture. They resemble the spherulites of some Hungarian liparites.

The obsidian is an almost absolutely pure, perfectly clear, light-brownish glass, less than 1 per cent of crystals being present, very small euhedra of alkali-feldspar and rare augite microlites, but no cossyrite. No perlitic cracks are seen in these or any of the glassy groundmasses.

Chemical composition.—Four analyses by myself and four by Foerstner are given:

ANALYSES OF HYALOPANTELLERITE

(KHAGIARAL VARINGOSE-GRORUDOSE)

	A	B	C	D	E	F	G	H	A*a*	B*a*	C*a*	D*a*
SiO_2.....	69.91	66.07	69.33	67.85	69.61	68.75	68.33	67.89	1.165	1.101	1.156	1.131
Al_2O_3....	8.58	11.74	8.62	12.87	8.02	5.91	10.94	11.53	.084	.115	.084	.126
Fe_2O_3....	1.81	2.05	2.65	1.84	7.17	5.81	3.74	4.51	.011	.013	.017	.012
FeO.....	5.86	5.88	5.52	4.54	2.83	5.33	5.41	4.52	.082	.082	.076	.063
MgO.....	0.28	0.13	0.52	0.30	0.65	0.08	0.16	0.62	.007	.003	.013	.008
CaO.....	0.33	0.46	0.52	0.17	0.88	2.11	1.36	1.51	.006	.008	.009	.003
Na_2O....	6.41	6.89	4.78	6.03	7.47	7.52	7.09	5.79	.103	.111	.077	.097
K_2O.....	4.71	4.80	4.71	4.83	2.88	4.28	4.08	3.71	.050	.051	.050	.051
H_2O+...	0.22	0.43	2.35	0.13	0.74	n.d.	n.d.	0.33	....	....	....	....
H_2O-...	0.13	0.03	0.27	0.02	n.d.	n.d.	n.d.	....	....	....	....	....
TiO_2.....	0.75	0.92	0.85	0.83	n.d.	n.d.	n.d.	n.d.	.009	.012	.011	.010
ZrO_2.....	....	0.12	....	....	....	....	....	....	....	....	....	....
P_2O_5.....	0.16	0.18	....	0.08	n.d.	n.d.	n.d.	n.d.	.001	.001	....	.001
SO_3.....	....	0.23	....	....	....	....	....	....	....	....	....	....
MnO....	0.24	0.16	0.27	n.d.	n.d.	n.d.	n.d.	n.d.	.003	.002	.004	....
BaO.....	....	none	....	...	....	....	CuO = 0.25	....	....	....	....	....
	99.39	100.09	100.39	99.49	100.25	100.02	101.36	100.41	....	....	....	....

A. Gelkhamar. H. S. Washington, analyst.
B. Ḳhagiar. H. S. Washington, analyst.
C. Cantina Ziton. H. S. Washington, analyst.
D. Obsidian. Costa Zeneti. H. S. Washington, analyst.
E. Khagiar. H. Foerstner, analyst. *Zeits. Kryst.*, VIII (1884), 173.
F. Cuddia Randazzo. H. Foerstner, analyst. *Zeits. Kryst.*, VIII (1884), 179.
G. Khania. H. Foerstner, analyst. *Zeits. Kryst.*, VIII (1884), 170.
H. Monte Sant' Elmo. H. Foerstner, analyst. *Zeits. Kryst.*, VIII (1884), 186.
A*a*. Mol numbers of A. B*a*. Mol numbers of B.
C*a*. Mol. numbers of C. D*a*. Mol numbers of D.

These analyses resemble those of the preceding type in most respects, but differ in the higher soda and in the relative amounts of the iron oxides, ferrous oxide being here largely in excess of ferric, both in percentage and molecularly, though the sums of the two in both types remain about the same. Foerstner's analyses show the same relations to mine as in the previous cases, a tendency to lower alumina, and higher ferric oxide, magnesia, lime, and soda. Except in E his ferrous oxides are higher than ferric, or nearly so. I could detect none of the copper noted by him in any of my rocks.

Norms.—The norms of my analyses are as follows:

	A	B	C	D
Q	28.38	14.70	28.02	15.36
Or	27.80	28.36	27.80	28.36
Ab	17.82	33.54	17.82	39.30
Ac	5.08	6.01	7.85	5.54
Ns	7.08	4.15	3.17	1.22
Di	0.75	1.24	2.16	....
Hy	10.34	9.01	9.28	7.80
Il	1.37	1.82	1.67	1.52
Ap	0.34	0.34	....	0.34
	98.96	99.17	97.77	99.44
Rest	0.35	0.81	2.62	0.15
	99.31	99.98	100.39	99.59

These norms are noteworthy because of the large excess of soda, expressed as sodium metasilicate, over alumina and ferric oxide, which they show. This finds expression modally in the presence of cossyrite, and study of the thin sections shows that, in a general way, the amount of cossyrite present is correlated with that of sodium metasilicate in the norm. The analysis of cossyrite by Dittrich[1] yields nearly 9 per cent of sodium metasilicate, and it is also very high in ferrous oxide. These two factors determine the chief chemical differences between the two main types of pantellerite—the one with dominant aegirite and the other with dominant cossyrite among the mafic minerals.

These norms show that all the rocks are in dosalane. The Gelkhamar and Cantina Ziton rocks fall in varingose, transitional

[1] Cf. J. Soellner, *Zeits, Kryst.*, XLVI (1909), 539.

to grorudose, and the subrang is almost dopotassic through the very small amount of alumina present, II.3(4).1.(2)3. As this dopotassic subrang is as yet unknown, they may best be called grorudose-varingose. The others fall centrally in grorudose, II.4.1.3.

It will have been noted that none of the pantellerites analyzed by me fall in the subrang pantellerose, II. 4.1.4. This name was chosen for the subrang because of two analyses by Foerstner, which were then the only ones available.[1] As we shall see, however, these must be considered to be incorrect, and this case may serve as an example of the danger of basing rock names depending on chemical characters on any but reliable analyses. Further examples will be found in a forthcoming second edition of my *Collection of Rock Analyses.*

Mode.—The rock is so dominantly hyaline that the mode is indeterminate. It may be of interest to note, however, that if the lava had wholly crystallized the rocks would have had about the following composition: quartz 15 to 25, soda-microcline 45 to 55, cossyrite 15 to 25, aegirite or aegirite-augite 5 to 10. It is evident that a large proportion of the aegirite and cossyrite molecules would have been among the last to crystallize out. J. Soellner,[2] through an analysis by Dittrich, has shown that the olivine from this type of pantellerite is an almost pure fayalite, with FeO:MgO=10:1. The analysis and the norm of the olivine-bearing pantellerite C confirm this, the ratio being 6:1.

It seems to be preferable to use the name hyalopantellerite for this type rather than to coin a new name. If the latter be deemed advisable that of *khagiarite* might be suggested.

BASALT (CAMPTONOSE)

Occurrence.—Basalts, all of which belong to the subrang camptonose (III. 5.3.4), are found only in the northwest corner of the island, being the products of eruption of the last phase of the volcano. They poured out from small cones—Cuddie Ferle, Bruciate, Monti, Rossi, Nera, and through the pantellerite on the

[1] Cf. H. S. Washington, *Prof. Paper U.S.G.S. 14*, 1903, p. 221.

[2] J. Soellner, *Zeits. Kryst.*, XLIX (1911), 144.

north slope of Monte Sant' Elmo—forming rather extensive flows from 2 to 5 meters thick, and accompanied by much scoria and ash. There are a few basaltic dikes cutting yellow pantellerite tuffs but these are of small size.

Megascopic characters.—These basalts present no unusual features and are of the common type, dark-gray to black rocks, aphanitic or nearly so, with few small phenocrysts of dark-green augite and sometimes yellow olivine and fewer of feldspar. Most of the specimens are slightly vesicular and scoriaceous *aa* flows are common. The scorias are generally black, but sometimes reddish. About Cuddia Ferle small, ovoidal or fusiform bombs are found.

Microscopic characters (*Figs. 10 and 11*).—The phenocrysts of feldspar are anhedral and either stoutly prismatic or tabular, parallel to *b* (010). Nearly all of them are of labradorite, about Ab_1An_1, with the usual twinning lamellae, and a few show a border of more sodic material. There are some phenocrysts of soda-microcline, especially in lava from Cuddia Ferle, which carry few inclusions, mostly of glass. Subhedra of colorless augite, often in clusters, are fairly common. Olivine phenocrysts are rather more common than those of augite in the Ferle basalt, but olivine is wanting in that from Sant' Elmo. It is highly euhedral, very fresh, with few inclusions of magnetite. The rock analysis and norm show that it is an olivine and not fayalite.

The groundmass is typically basaltic, composed largely of thin plates of labradorite, grains of colorless augite, and considerable magnetite. In the larger flows it is holocrystalline. No nephelite is to be found.

A dike of basalt which cuts the yellow pantellerite tuffs at the northeast end of Costa Zeneti merits a few words of description. It has an east-west trend, approximately radial toward Cuddia Ferle, which is about one and a half kilometers to the west. It is vertical, from 10 to 30 cm. wide, and has hardened and blackened the rather incoherent tuff for about 5 cm. on either side. The rock itself is jet black and aphanitic, very minutely vesicular, more coarsely so toward the borders, and is almost free from phenocrysts, very small (1–2 mm.) feldspars being sparingly present. In the section thin tables of labradorite are prominent, augite

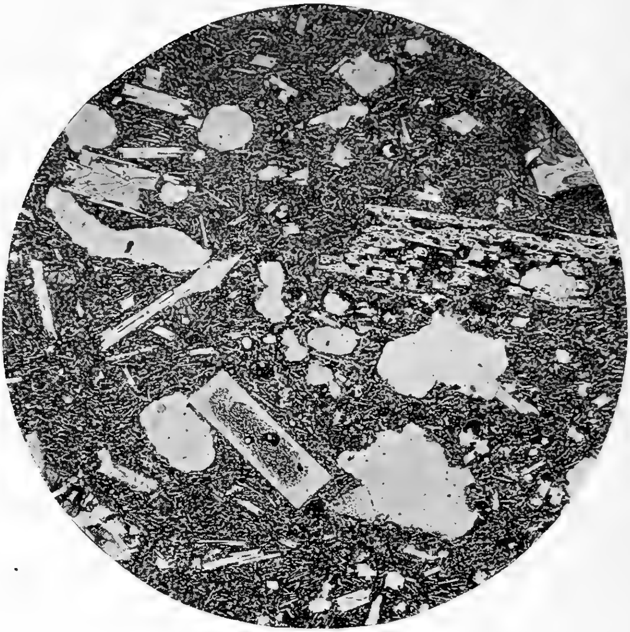

FIG. 10.—Basalt, Cuddia Ferle. × 20

FIG. 11.—Basalt, dike, Costa Zeneti. × 20

anhedra are not common and there is very little olivine. These lie in a base of glass which, black under low powers, is seen under high to be thickly crowded with brown and black globulites. In this respect, as well as in the character of the feldspars, it is much like the basalts of the submarine eruptions of 1831 and 1891,[1] which it also resembles chemically.

Chemical composition.—Three analyses of these basalts, with two of the submarine lavas, and two by Foerstner, are given in the table.

ANALYSES OF BASALT

(CAMPTONOSE)

	A	B	C	D	E	F	G	*Aa*	*Ba*	*Ca*
SiO_2	46.40	46.22	45.72	44.83	48.97	49.87	49.35	0.773	0.770	0.762
Al_2O_3	14.34	12.23	12.45	11.73	16.37	14.80	15.71	.141	.120	.122
Fe_2O_3	4.09	4.91	1.57	1.35	1.33	8.25	7.44	.026	.031	.010
FeO	8.22	7.71	12.01	11.79	8.56	6.88	6.96	.114	.107	.167
MgO	7.00	6.74	5.29	5.50	6.22	6.77	5.71	.175	.169	.132
CaO	9.85	9.86	9.58	9.63	7.49	9.36	9.80	.177	.176	.171
Na_2O	3.59	3.39	3.40	3.34	4.09	2.81	2.96	.058	.055	.055
K_2O	1.00	1.13	1.08	1.40	1.72	0.68	1.31	.011	.012	.011
H_2O+	0.14	0.17	0.40	0.81	0.38	0.45	0.49	....	....	....
H_2O-	0.08	0.05	0.01	0.10	0.08	n.d.	n.d.	....	....	....
TiO_2	4.54	5.68	6.43	6.88	3.95	n.d.	n.d.	.057	.071	.080
ZrO_2	none	....	....	....	....	....	....	....	....	....
P_2O_5	0.85	1.46	1.54	2.14	1.04	n.d.	n.d.	.006	0.010	.010
SO_3	0.12	....	....	....	....	....	....	....	....	....
MnO	0.25	....	0.16	0.20	0.06	n.d.	n.d.	0.003	....	0.002
NiO	....	....	0.15	....	0.08	....	....	....	....	....
BaO	0.09	....	....	....	....	....	....	....	....	....
SrO	0.03	....	0.03	....	....	....	....	....	....	....
	100.59	99.55	99.82	99.70	100.34	99.87	99.73	....	....	....

A. Cuddia Ferle. H. S. Washington, analyst.
B. Monte Sant' Elmo. H. S. Washington, *Q.J.G.S.*, LXIII (1907), 74.
C. Dike, Costa Zeneti. H. S. Washington, *Q.J.G.S.*, LXIII (1907), 74.
D Foerstner Volcano (1891). H. S. Washington, *Am. Jour. Sci.*, XXVII (1909), 145.
E. Graham Island (1831). H. S. Washington, *Am. Jour. Sci.*, XXVII (1909), 138.
F. San Marco. H. Foerstner, analyst. *T.M.P.M.*, V (1884), 393.
G. Cuddie Monti. H. Foerstner, analyst. *T.M.P.M.*, V (1884), 393.
Aa, *Ba*, *Ca*. Mol. numbers of A, B, and C, respectively.

The analyses of the Pantellerian basalts are much alike, and except for the rather low silica and high titanium and phosphorus, are not specially noteworthy. The only marked difference is in the iron oxides. While the sum of both is about the same in all, in

[1] H. S. Washington, *Am. Jour. Sci.*, XXVII (1909), 131.

the flows A and B the molecular amount of FeO is about four times that of Fe_2O_3, but in the dike C it is seventeen. In this respect the dike basalt resembles the basalts of the two submarine eruptions D and E, the former close to the harbor of Pantelleria and the latter about 33 miles to the northeast. It will be seen that C and D are almost duplicates, while E differs considerably in the silica and other respects. These relations of the iron oxides give rise to the idea that the ferrous oxide has been prevented from oxidation in the dike and the submarine eruptions—a point which has been discussed in a previous paper.

Norms.—The norms of the Pantelleria basalts are as follows, those of the submarine ones having been given in the paper cited:

	A	B	C
Or	6.12	6.67	6.12
Ab	28.30	28.82	28.82
An	20.02	14.73	15.57
Ne	1.14	.....	.....
Di	18.81	19.54	18.77
Hy	.....	8.06	5.74
Ol	9.32	0.28	6.29
Mt	6.03	7.19	2.32
Il	8.66	10.79	12.16
Ap	2.02	3.36	3.36
Rest	0.46	0.22	0.69
	100.88	99.66	99.80

These norms place all three Pantellerian basalts in camptonose, III. 5.3.4, a subrang in which many basalts and gabbros fall. It will be noted that, in spite of the low silica, nephelite is not present in the norm, except to a slight extent in the Ferle rock, and it can hardly be said that these basalts have the trachydoleritic character assigned them by Rosenbusch (p. 1357). It will also be observed that these norms correspond with the microscopic characters, the Ferle rock carrying considerable olivine, which is wholly absent from the Sant' Elmo basalt.

Mode.—It is impracticable to estimate the mode by Rosiwal's method because of the fineness of the grain. Apart, however, from the small amount of alumina (to be taken from normative anorthite) which enters the augite the mode is essentially norma-

tive, and the modes of the two basalts of Ferle and Sant' Elmo may be roughly stated as follows, the orthoclase being reckoned in with albite. It is possible that the nephelite molecule of the norm exists as carnegieite in the feldspar.

	I
Ab_1An_1	50
Nephelite	1
Augite	22
Olivine	9
Ores	14
Apatite	2
	100

	II
Ab_3An_2	48
Augite	32
Ores	17
Apatite	3
	100

A STUDY IN THE PETROLOGY OF SEDIMENTARY ROCKS[1]

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INTRODUCTION

Since the introduction of the petrographic microscope about the middle of the last century a great mass of detailed information concerning the composition of rocks has been accumulated, but by far the greater part of this concerns igneous rocks alone. Metamorphic rocks have received their due share of attention, but sedimentary rocks have been almost entirely neglected. Thus, most university courses in petrology touch on the last-named class only in a more or less perfunctory way, and similarly in practical work the geologist generally confines the use of his microscope chiefly or entirely to the igneous rocks. This disparity is the more notable because of the fact that sedimentary rocks preponderate at the earth's surface, and while the study of their petrology does not seem to possess the fascination which attracts the students of igneous rocks, their areal importance is certainly such as to command attention. This paper is a preliminary and more or less tentative discussion of the value of microscopic work in the correlation of stratified rocks, with an example of an application recently made by the writer. Mr. D. F. Hewett, of the United States Geological Survey, has been working along similar lines, and the writer takes this opportunity of expressing his appreciation of Mr. Hewett's many valuable suggestions.

Sediments, by their very nature and the manner of their derivation, do not lend themselves readily to the taxonomic principles which we apply to igneous rocks, nor can their almost infinite variations be traced and interpreted as clearly. It is perhaps for this latter reason that geologists have in general been content to classify a rock as sandstone, or shale, or arkose, without attempting

[1] Published by permission of the Director of the U.S. Geological Survey.

to inquire very closely into the proportions of its component minerals or the shape of their grains. Many sedimentary rocks, it is true, have been examined and described as lithologic types for educational purposes,[1] or because of some peculiarity in distribution or occurrence,[2] and there are a few instances in which they have been carefully studied for economic reasons,[3] but little work of a genetic character, directed upon the rock as part of a mass or formation rather than as a more or less fortuitous rock type, has been done.

THE IMPORTANT LINES OF RESEARCH ON SEDIMENTARY ROCKS

During the past decade attention has been directed to sedimentary rocks by the masterly studies of Johannes Walther in Germany and the amplification of his work in this country by Barrell, Grabau, and others. These geologists have, however, dealt almost entirely with the stratigraphic relations of the beds, and such structural features as cross-bedding, mud cracks, etc. In endeavoring to ascertain the manner of deposition of the rock, whether for example as a deep-sea deposit or a river sediment, a delta or playa lake, they have assigned somewhat minor importance to its petrology, considering chiefly its broader megascopic characters. Considerable work has also been done upon the transportation of sedimentary material by water and by wind[4], and the consideration of criteria by which the amount of such movement may be estimated. Thus W. H. Scherzer[5] has constructed a classification of sand grains based largely on their size, their degree of angularity and the amount of

[1] Such descriptions are given by Diller, *Bull. U.S. Geol. Survey No. 150*, 1898; by Harker, *Petrology for Students;* by Kemp, *Handbook of Rocks;* by Hatch and Rastall, *Petrology of the Sedimentary Rocks;* and by the authors of most of the other textbooks on lithology.

[2] See for example L. Cayeux, "Structure et classification des Gres et Quartzites," *Congres geol. internat. C.R.*, 10th Session, 1906, pp. 1211–22.

[3] See for example, C. B. Berkey, *Bull. New York State Mus., No. 146*, 1911, pp. 124–48.

[4] See for a summary, with very complete lists of references, E. E. Free, "The Movement of Soil Material by the Wind," *Bull. Bureau of Soils, U.S. Dept. Agric., No. 68*, 1911.

[5] "Recognition and Classification of Sand Grains," *Bull. Geol. Soc. Amer.* (XXI), 1910, 625–62.

their polish. Finally, while relatively little detailed study of the mineral composition has been made, we have a fairly definite idea of the minerals which commonly make up clastic rocks, and, in the case of feldspar at least, some conception of its genetic significance.

It is the belief of the writer that the three lines of research mentioned in the preceding paragraph, viz., upon the broad structural features, the shape of the grains, and the mineral character of the grains, may profitably be combined, and that the value of the results obtained by any one is greatly enhanced when considered in relation to the other two. The importance of a close study of the structural features of a clastic rock has been amply demonstrated by Barrell and others. The criteria given by Scherzer, when it is possible to apply them, are of similar value in determining the manner of deposition of the sediment and something of its history prior to deposition. Finally, the mineralogical composition of the rock, though in many cases having no apparent significance, is in others decidedly important. When a sandstone is made up practically entirely of quartz, as is the St. Peter sandstone, the significance of this fact is immediately recognized and taken into account in considering its history and derivation.[1] Thus, C. P. Berkey considers the St. Peter sandstone of eolian (sand dune) origin, because of the fact that it contains 98 to 99 per cent of quartz, largely in rounded grains of a nearly uniform size. Certain formations in the east, such as the Newark group, have been assigned a continental origin partly because of their arkosic character and red color, and this also illustrates a partial application of these principles. When the composition is less apparent to the naked eye, however, the importance of its determination may not be so evident; and very little is known of the exact mineral constituents of the great thickness of Cretaceous and Tertiary strata in the Great Plains and Rocky Mountain provinces.

Aside from the importance of such data in determining the history and origin of a rock they may in some cases have a distinct correlative value. Thus, in the instance of the Lebo shale member of the Fort Union formation described below, the writer was able to

[1] See "Paleogeography of St. Peter Time," *Bull. Geol. Soc. Amer.*, XVII (1906), 229–50.

correlate the strata by the varying, though generally small, amount of andesitic tuff or ash which it contains, the Lebo member at the type locality consisting chiefly of andesitic material. Similarly if a formation, or some particular stratum of a formation, were known to contain tourmaline, or a large amount of mica, or spherulitic glass, or some other distinctive constituent, this information might prove a valuable auxiliary in correlation to stratigraphic and paleontologic evidence. Though the instances last cited are doubtless uncommon it is probable that ash is rather widely distributed through the Cretaceous and Tertiary rocks of the west, and it may prove to be an aid to correlation in many cases. Moreover, even where conditions are not favorable to using the petrology in this way it is possible that it may throw light on the exact position of a doubtful formation boundary. Thus, D. E. Winchester, United States Geological Survey, believes that evidence of this kind may lead to fixing the lower limit of the Mesaverde formation in the Zuni Indian Reservation, New Mexico, where by reason of a lack of diagnostic fossils at the critical horizon the exact base of the formation cannot be otherwise located. The case of the Lebo shale described below furnishes a simple example of the value which petrologic evidence may have.

THE LEBO SHALE MEMBER OF THE FORT UNION FORMATION IN EASTERN MONTANA

General statement.—During the summer of 1911 the writer examined for the United States Geological Survey an area in eastern Montana known as the Little Sheep Mountain coal field[1] which extends about 60 miles westward from the town of Terry, on the Yellowstone River. In contiguous areas on the east and south the strata had been mapped as Fort Union and Lance.

About 850 feet of the upper or yellow strata of the Fort Union formation are exposed in the Little Sheep Mountain field, the age of these rocks being definitely established by paleontological evidence. The beds are made up of sandstone, sandy shale, and clay shale, generally soft and in many places incoherent, and commonly yellow

[1] G. S. Rogers, "Little Sheep Mountain Coal Field," *Bull. U.S. Geol. Survey No. 531*, 1913 (in press).

in color. The areas in which these beds are exposed are gently rolling prairies, or less commonly hills, with bare slopes. Directly across the river from Terry the yellow beds of the Fort Union formation are underlain by the Lance formation, of which only about 150 feet are exposed. This formation resembles the Fort Union in every way, except that there are perhaps more beds which are light gray in color instead of yellow. The contact between the two formations is marked by a coal bed (known as bed U) which is persistent through the eastern part of the field.

At a point about five miles west of Terry, however, the strata for 200 feet above coal bed U are dark gray in color and strikingly dissimilar to both the yellow Fort Union and the Lance (see Fig. 1). This dark gray member is composed of very irregularly deposited masses of shale with occasional arkose sandstones. Except for the numerous irregular and discontinuous layers of hard ferruginous concretions, and for a few fairly hard and generally massive sandstones, the beds are always soft and practically incoherent. The outcrop of this member, which traverses in a broad belt the entire field west of this locality, is characterized by the formation of badlands so rough in many places as to be almost impassable. This land is given over largely to grazing purposes, and even in the comparatively level creek bottoms it is very poor for agricultural purposes. The general sterility of this member, its tendency to form badlands, and its decidedly dark gray color all combine therefore to make it easily identifiable in the field.

For the reasons given below this mass of dark shale is believed to represent the Lebo shale member of the Fort Union formation. The Lebo was first described on Lebo creek in the vicinity of the Crazy Mountains,[1] about 175 miles west of the Little Sheep Mountain field. It is there interpreted as an outfingering of the Livingston formation,[2] which is composed of andesitic material, both detrital and tuffaceous, and which covers considerable areas west and south of the Crazy Mountains. This intercalated fan extends

[1] R. W. Stone and W. R. Calvert, "Stratigraphic Relations of the Livingston Formation of Montana," *Econ. Geology*, V, No. 6, September, 1910, p. 752 ff.

[2] See W. H. Weed, "The Laramie and the Overlying Livingston Formation in Montana," *Bull. U.S. Geol. Survey, No. 105*, 1893.

east to the Bull Mountains, about 50 miles west of the area under discussion, where it was mapped by C. T. Lupton.[1] Between this area and the Little Sheep Mountain field the beds are raised in a gentle anticline which exposes the Pierre shale, and the Fort Union and Lance are eroded, so that there is no way of actually tracing the Lebo member from the one field to the other.

Stratigraphic relations and structural features of the Lebo shale member.—The distinctive appearance of this member facilitated the recognition of the fact that it is wedge or fan-shaped. In the eastern part of T. 12 N., R. 51 E., directly opposite Terry, it is lacking. Coal bed U, which is taken as marking its base, is here

FIG. 1.—View of badlands in T. 12 N., R. 50 E., P.M., Montana, looking north; and showing the yellow beds of the Fort Union formation in the background overlying the gray Lebo shale member.

directly overlain by the yellow beds of the Fort Union and underlain by the light yellowish gray beds of the Lance. In the northeast quarter of sec. 9, T. 12 N., R. 51 E., there are about 12 feet of dark-gray shale above this coal bed. A half-mile to the west the strata above it are yellow and gray, alternating in about equal quantity; a mile farther west there are 200 feet or more of dark-gray material above it with only occasional beds of dirty yellow (see Fig. 1). In sec. 29 of T. 11 N., R. 50 E., seven miles southwest of the

[1] C. T. Lupton, "The Eastern Part of the Bull Mountain Field, Montana," *Bull. U.S. Geol. Survey, No. 431*, 1909, pp. 163–89.

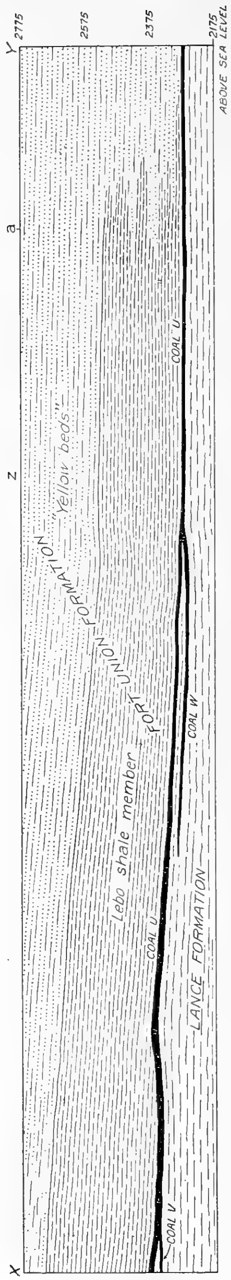

FIG. 2.—Diagram showing stratigraphic relations of Lebo shale member of Fort Union formation in Little Sheep Mountain coal field. Compiled from sections made along a line running 11 miles northeast from the mouth of Custer Creek (point X) to point Z; thence six miles east to a point opposite Terry (point Y). At point *a* a detailed section was made which showed the alternation of yellow and dark-gray strata as indicated.

last mentioned locality there are 250 feet of these dark shales between coal U and the yellow phase of the Fort Union; and on Custer Creek, seven miles farther southwest, about 340 feet. Beyond this there was no opportunity for measurement, and 20 miles farther west the coal which marks the base of the Lebo runs out of the district. The Lebo is therefore fan-shaped (see Fig. 2), of a thickness unknown in the western part of the field, but probably not greater than 350 or 400 feet; and reaching its eastern limit in this area in sec. 11, T. 12 N., R. 51 E., opposite Terry.

A noticeable structural feature of the Lebo member is the very irregular character of the beds, which change rapidly in a horizontal direction. A measured stratigraphic section represents the strata in one place only; at a distance of 1,000 feet on either side many of the beds change in color and often in texture. Scattered throughout the member are numerous lenses of a white and sandy material; these are commonly less than 2,000 feet in length and perhaps 60 feet in thickness, and are often only 200 feet long and 10 or 20 feet thick. In many cases they lie obliquely to the surrounding beds (Fig. 3) and are themselves strikingly cross-bedded (Fig. 4). The latter feature, together with

ripple-marks and mud cracks, is very common throughout the whole of the Lebo. The lenticular and irregular character of these strata extends to their coals as well, which are generally dirty, and, with the exception of bed U, of no great extent.

Petrologic evidence—mineralogical composition and character of grains.—The Lebo shale on the northeastern flank of the Crazy Mountains is described as a derivative of an andesite. Microscopic examination showed that certain facies are nearly pure tuffs, but that generally a considerable amount of plagioclase is present and

FIG. 3.—View in badlands on Custer Creek showing irregular character of the Lebo shale sediments, and the intercalation of lenses of white sandy clay which contains about 50 per cent andesitic ash, sec. 11, T. 11 N., R. 49 E., P.M., Montana.

that the whole is set in a fine chloritic groundmass. Fragments of hornblende and augite are also frequently found, and in places there is a considerable admixture of quartz. Eight thin sections were made of the more coherent members of the dark shale of the district discussed in this paper and in addition a number of sections of incoherent material were prepared without grinding; and all these were examined by the writer. Two of the thin sections were fine-grained dark gray shale, so fine in fact that the microscope revealed no recognizable grains. They seem to consist of kaolin stained

brown by iron oxide, and the shale may have been derived from nearly any kind of an igneous rock. Three of the sections were made from the grayish sandy lenticular material mentioned above, collected at two places about 10 miles apart in T. 9 N., Rs. 42 and 43 E. They are all decidedly tuffaceous in character and contain about 50 per cent of angular, subangular and rounded fragments of a brown volcanic glass, commonly more or less devitrified and altered. Quartz in small angular grains makes up about 40 per cent, and the remainder consists chiefly of kaolin and chlorite.

FIG. 4.—Cross-bedding in white sandy clay facies of the Lebo shale member, sec. 30, T. 11 N., R. 49 E., P.M., Montana.

Though the quartz indicates a considerable admixture of foreign material, this would be expected at a distance of 175 miles from the supposed source. One slide was made from a fine-grained, sandy, yellow-gray bed; this also revealed the presence of some volcanic glass, but the rock consisted chiefly of very small fragments of chloritic material with considerable quartz. Finally two sections of sandy shale partially baked by the action of a burning coal bed were examined. Their original character was, of course, largely destroyed, but fragments of a fresh green augite were identified in both of them. These descriptions hold also for the slides prepared

from the incoherent material; several were too fine-grained to permit of satisfactory identification, but the remainder contained varying quantities of glass, commonly badly altered. The sandy white material is thus derived directly from andesitic effusive material; all of the other rocks examined which were coarse enough to allow of study indicate a derivation, in large part at least, from a basic igneous rock; the shale is in general too fine to warrant an opinion as to its origin, but its evidence is not adverse. Furthermore, specimens of the yellow Fort Union above and of the Lance below were examined and all indicate a probable derivation from a much more siliceous rock; at least it may be said that they differ decidedly from the dark shale.

Owing to the fact that most of the important constituents of these rocks—glass and ferro-magnesian minerals—are prone to comparatively rapid alteration the evidence as to the shape of the grains in this instance cannot be satisfactorily obtained. The feldspar grains are in general nearly or quite fresh and are angular. The quartz is commonly in decidedly angular grains and only a few were noticed which were subangular or rounded. Similarly in the case of the glass it seems that the fresher the grain the more angular it is, some being found which were fairly fresh and distinctly angular. While these rocks are not favorable for a detailed study of the shape of the grains it may be said that they show the complete assortment as to size which characterizes Scherzer's aqueous type, but with the angularity which is regarded as diagnostic of the volcanic, glacial and residual types. Taking the mineral composition into account therefore they may be classified as aqueo-volcanic rocks.

Interpretation.—Because of this concurrence of the stratigraphic and petrologic evidence therefore it seems proper to corre ate these strata with the Lebo member. According to this hypothesis a large part of the material has been transported from the Crazy Mountains, although a considerable increment of foreign detritus has been received along the route. The striking cross-bedding and the decided lenticularity and lack of persistence of the beds argue for a fluvial origin, while the angularity of the grains themselves and their assortment as to size offer a similar suggestion and preclude the possibility of any long eolian transportation. It is possible that the

lenses of the white sandy tuffaceous material described above may represent the ancient stream courses. These lenses are numerous and generally of small size; in many cases they lie at a small angle across the strata and are themselves always strikingly cross-bedded (see Figs. 3 and 4). It would not be expected that recent erosion of the badland type would lay bare an old river course with its meanders for any great distance; the recent gulleys would cut across at all angles and the exposures of the old alluvium would pinch out abruptly. The shorter lenses would then represent an approximate cross-section of the old channel, while the longer ones might be interpreted as more or less complete approaches to a longitudinal section.

APPLICABILITY OF THESE PRINCIPLES

Lack of exactness in our present knowledge.—The application of the principles above outlined is naturally limited to certain formations, and is at the present time hampered by our comparatively small knowledge of the petrology of clastic rocks. The lack of detailed microscopic study is making itself felt in the deplorable looseness of our definitions of the types. A committee on the nomenclature of the more common types of sedimentary rocks was recently appointed in the United States Geological Survey, and in the course of a rather exhaustive search through the literature in an endeavor to find some basis for standardizing and delimiting the types in common use encountered a surprising discordance of opinion. Shale, clay, graywacke, arkose, argillite, etc., are differently defined in different books and in some cases not defined at all. With so little literature on the exact composition of sedimentary rocks and with the very basis of the lithology of these rocks in this condition it is difficult to say how great an aid microscopic work will prove in solving the problems of correlation or in reconstructing the conditions under which a sediment was laid down. At the present time it would seem that in many, if not most cases, such a study would have no immediate and practical value, but on the other hand, there are certainly many problems in which it might be used with direct advantage, as in the instance given above.

The lack of exactness in our present knowledge may be further illustrated by the following example, which represents another and

somewhat different application of these principles. The writer in the course of an examination of a portion of the ceded lands of the Crow Indian Reservation, Montana, during the past summer, followed the outcrop of a coal bed in the Lance formation for a distance of about thirty miles; and throughout this distance the bed contains a parting of material which closely resembles a brown carbonaceous sandstone. This parting varies only from three-fourths of an inch to $1\frac{1}{4}$ inches in thickness, and its constancy and persistence proved a decided aid in recognizing and correlating the coal bed. Such characters are exceptional in the Tertiary and Cretaceous continental deposits of the west, and the writer was prompted therefore to examine microscopically several specimens of the parting. In thin section this material proved to be, not a clastic sandstone as supposed, but to be a nearly pure aggregate of delicate mineral crystals, which undoubtedly formed *in situ*. The optical characters correspond to those of Leverrierite.[1] The mineral is now being more carefully examined and analyzed and the writer hopes to discuss it in a later paper.

It is apparent of course in this instance that the practical value of the small layer did not depend on microscopic examination, since use was made of it in correlation before its real nature was known. Microscopic study in this case merely served to explain its persistency and homegeneity, the characters which rendered it of value in the field, and to throw light on its origin and its relation to the coal bed and other strata. Moreover, the formation of such a pure mineral deposit in the midst of a heterogeneous mass of largely continental sediments is certainly of scientific interest; and if it is, as the writer is inclined to believe, not an uncommon development, but merely one which lack of previous petrologic work has held us in ignorance of, its bearing on the accumulation and alteration of sedimentary rocks is manifestly important.

Practical difficulties.—The microscopic study of sedimentary rocks is attended by certain practical difficulties which the writer can attempt only to suggest. In the first place the fineness of the material and the extent of its decomposition are important obstacles to the study of shale. Where the grain is not too uniformly small,

[1] First fully described by P. Termier, *Ann. d. Mines*, XVII (1890), 272.

washing or floatation may be used, thus removing the finely divided and thoroughly hydrated—perhaps colloidal—material. If more elaborate methods are desired, recourse may be had to the elutriator, the electro-magnet, heavy liquids, etc.[1] These methods of course destroy the proportions of the constituents, but facilitate the study of the features—assortment, angularity, and polish,—which are really important to the consideration of the rock from a genetic standpoint, and they will in many cases be the most expedient. On the other hand it seems probable that certain very fine-grained shales and clays are largely made up of colloidal material, which may prove to be homogeneous in composition and to have more or less distinct optical properties, and in such cases it may be desirable to study it as a whole without attempting at first to ascertain the character of the mineral particles from which it was derived.

Secondly, the question of field criteria for recognizing the particular rocks likely to prove critical presents itself, since it is obviously impossible to make and examine a complete collection of all the variations in a series. It is patent, of course, that very fine-grained rocks, since they do not respond satisfactorily to our present elementary methods of study, are less likely to prove helpful than the coarser-grained varieties; and on the other hand that the presence of uncommon constituents in very coarse sandstones and conglomerates can usually be recognized without the microscope. The writer must confess his inability to suggest any definite rule, however, and believes that from the nature of the case none can be framed. Such a question must be left largely to the field geologist.

Finally, it seems desirable that the geologist who studies the rocks in the field should be the one to examine them microscopically. The petrology of a sedimentary rock is in most cases of little or no significance except when considered in relation to the structural and stratigraphic features. Furthermore, its exact horizon is generally important and the relation of the stratum to those adjoining; and such data will, of course, be noted by the collector in any case.

[1] See F. H. Hatch and R. H. Rastall, *Petrology of the Sedimentary Rocks*, 1913, Appendix on the Systematic Examination of Loose Detrital Sediments, by T. Crook.

There are many minor points, however, which the field geologist remembers, but which were considered of too small importance to write down at the time, and which may yet derive an unexpected significance from the results of a simple petrologic study. When possible therefore, it is advantageous for the field man to examine his own material.

SUMMARY AND CONCLUSIONS

The amount of petrologic work done on sedimentary rocks, especially the more or less incoherent Cretaceous and Tertiary rocks of the West has been comparatively small, and most of the study made has been directed toward the rock as a rock type, rather than as a part of the rock mass or formation. Of late years attention has been directed to the broader structural features of clastic rocks and much information concerning the manner of deposition has been accumulated. It is believed that petrologic study of the mineral constitutents and the character of their grains will prove an important aid in determining the history of the rock, and that such study may also lead to facts of value in correlation and in the fixing of formation boundaries. An area of dark-gray shale near Terry, Montana, was correlated with the Lebo shale in the Bull Mountains to the west, largely by petrologic evidence. In this particular instance the determining constituent was andesitic ash, but in other cases the presence of other more or less distinctive constituents may be found significant and of value in correlation. There are two apparent difficulties confronting a study of this kind: first, those arising from the fact that many sedimentary rocks are made up of badly altered minerals occurring in grains too small for satisfactory examination; and second, the difficulty of choosing the proper rocks for detailed study. The fact that our definitions of sedimentary rock types are very vague and loose is in itself an argument for more petrologic study; and while it is not probable that this work will be found to have a very broad application to correlation, as in the one instance described, it still seems that it may prove an important auxiliary in that direction to the other lines of research at our command, and will in addition shed valuable light on the history of the rock.

ON THE RELATIONSHIP OF THE SOUTH AFRICAN PERMIAN REPTILES TO THOSE OF RUSSIA

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Springs, South Africa

Professor Williston[1] has lately issued a paper entitled "Primitive Reptiles: A Review" in which he sums up the present state of our knowledge of the American Permian reptiles. More briefly he discusses the Permian reptiles of Europe; and has some references to the South African types. Williston deals only with the lower Permian reptiles, and as we know only very few reptiles from the lower Permian rocks of South Africa the references to our African types are brief. As, however, possibly he or some other will later be discussing Permian reptiles in general, some new facts which I wish to state will probably be welcomed. Williston is inclined to regard our Karroo beds which contain *Pareiasaurus* as Upper Permian, since the *Pareiasaurus* beds of North Russia are undoubtedly Upper Permian. In this I think he is incorrect.

In the Karroo we have a continuous series of shales and sandstones from the Droyha conglomerate which we may regard as basal Permian up to the Molteno beds which we know to be Rhaetic. Thus we have the whole Permian and Triassic periods represented by about 9,500 feet of strata. The whole thickness we can subdivide into zones as follows:

Burghersdorp beds	2,000 ft.
Lystrosaurus and *Procolophon* zone	2,000 ft.
Cistecephalus zone	1,000 ft.
Endothiodon zone	1,000 ft.
Pareiasaurus zone	1,000 ft.
Ecca beds	2,000 ft.
Droyha shales	500 ft.

[1] S. W. Williston, "Primitive Reptiles: A Review," *Journal of Morphology*, XXIII, No. 4, December, 1912.

The thicknesses of the various zones are only very approximate and vary considerably in different parts of the country. The Burghersdorp beds contain the following European genera *Trematosaurus*,[1] *Cyclotosaurus*, *Capitosaurus*, besides others allied to European Triassic forms and there can be no doubt that the beds are of Upper Triassic age. The *Lystrosaurus* and *Procolophon* zones may be regarded as corresponding to the Lower Triassic of Europe, though we have no genera corresponding to those of Europe.

All the zones from the *Cistecephalus* to the Droyha may be taken as representing the European Permian, and this is confirmed by the fact that the Russian "*Pareiasaurus*" zone corresponds, not with our *Pareiasaurus* zone, but with our *Cistecephalus* zone.

Anyone who is familiar with our typical South African *Pareiasaurus* and then looks at the Dwina Pareiasaurs will at once see that the resemblance is not striking; and had I found the Russian species at the Cape, I should have put it in a new genus probably. Just recently a new Pareiasaurian was discovered by Haughton in the *Cistecephalus* zone, and it has been described by Haughton and myself as a new genus, *Pareiasuchus peringaeyi*, and we have called attention to the fact that it resembles the Russian animals much more than does our older *Pareiasaurus*. But of much more importance than the doubtful *Pareiasaurus* is the Russian *Inostrausewia*. This is a huge carnivorous reptile something like our carnivorous types. But no known Therocephalians from our *Pareiasaurus* zone are the least like *Inostrausewia*.

Just recently we have got evidence that our Permian carnivora can be conveniently subdivided into two groups. The lower forms are the typical Therocephalians: the upper I am placing in a distinct group, the Gorgonopsia. It matters little whether this be regarded as a distinct family or suborder. I prefer to call it a distinct suborder. A paper is at present in the press dealing with the distinction of the groups. Though our small Gorgonopsian is known from the *Pareiasaurus* zone, it is in the *Cistecephalus* zone that the group becomes pre-eminent. A large South African type recently described as *Scymnognathus tigriceps* is possibly identical

[1] It is just possible *Trematosaurus* may be from the *Lystrosaurus* zone.

generically with *Inostrausewia*. Certainly it is closely allied, and certainly *Inostrausewia* is a Gorgonopsian.

If I were shown the Russian Dicynodonts and were told they had come from South Africa and were asked from what zone I thought they had come I should unhesitatingly say that they must come from the *Cistecephalus* zone. Nothing like them is known from any of the earlier zones and in the *Cistecephalus* zone we get Dicynodonts strikingly similar. I have therefore little hesitation in affirming that the Russian fauna of the Dwina is the fauna of our South African *Cistecephalus* zone, and this confirms the view I expressed eight years ago, that the *Cistecephalus* zone represents our most recent Permian beds and that our typical Pareiasaurs are Middle Permian. In the present state of our knowledge we may regard our Pareiasaurian genera distributed as follows:

Cistecephalus zone.................... *Pareiasuchus*, *Propappus*
Endothiodon zone........................ *Propappus*, *Anthodon*
Pareiasaurus zone............................. *Pareiasaurus*

SOME PARTLY DISSECTED PLAINS IN JO DAVIESS COUNTY, ILLINOIS[1]

ARTHUR C. TROWBRIDGE
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Jo Daviess County is the northwesternmost county in Illinois and adjoins northeastern Iowa and southwestern Wisconsin. The county is partly covered by the Galena and Elizabeth topographic sheets of the United States Geological Survey. The topography of this county occupying the southern part of the driftless area has remained unaltered by the ice invasion and is still exposed for physiographic study. The writer, in company with E. W. Shaw and B. H. Schockel, spent a large part of the field season of 1910 in Jo Daviess County in co-operative work between the United States Geological Survey and the Illinois Geological Survey, and the following paper is one result of that work.

Rock formations appearing at the surface in the district are of Ordovician and Silurian age, and are classified as follows:

Name of Formation	Kind of Rock	Thickness
Niagara	Dolomite	140 feet
Maquoketa	Shale	108–209 feet
Galena	Dolomite	240 feet
Platteville	Limestone	50 feet

All of these formations occur at the surface over wide areas, with the exception of the Platteville, which is found only in the valley of Galena River in the northern part of the district. The strata have a general dip to the southwest of about 17 feet to the mile, and on this monoclinal structure are a series of slight, hardly noticeable anticlines and synclines.

The most conspicuous topographic feature in the county, aside from the bluffs of the Mississippi Valley, is a more or less

[1] Published by permission of the Director of the Illinois Geological Survey.

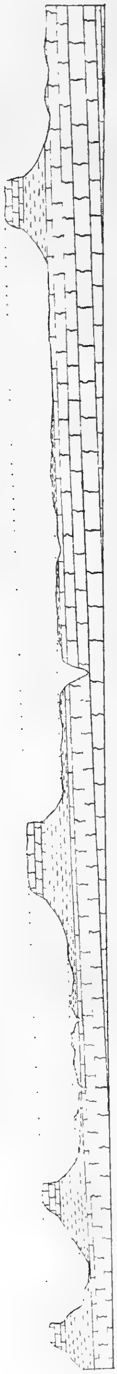

Fig. 1.—A diagram showing the relations of the Niagara and Galena plains to each other and to the rock structure of the district. The upper dotted line represents the Niagara plain, and the lower dotted line the Galena plain. The uppermost rock formation is Niagara dolomite and the lowermost is Galena dolomite. Between the two is the Maquoketa shale, represented by dashes.

extensive and definite plain midway between the skyline and the valley bottoms. Its surface is broken by mounds and ridges above it, and by many sharp valleys below it. For convenience this may be called the *intermediate plain.* The mounds and ridges which stand on the intermediate plain and whose tops form the upland come up to a somewhat common level, in such a way that if the low land were filled up to their tops the region would be a nearly flat plain. The upper dissected plain lies everywhere on the Niagara dolomite, and the intermediate plain follows more or less closely the surface of the Galena dolomite; hence the upper plain is here called the *Niagara plain* and the intermediate surface the *Galena plain.* These two plains, the first now almost entirely dissected and the latter somewhat but less so, constitute the problems of this paper. Their general relationships are shown in Fig. 1.

The Niagara plain was known to Hershey[1] as "Peneplain No. 1," and he considered it to be a true peneplain partly dissected, of Cretaceous age. Bain[2] mentions the plain and seems to agree with Hershey concerning it. The upper plain was also known to Grant and Burchard[3] who state that "the facts observed

[1] *Am. Geologist,* XVIII, 75–78.

[2] *Bull. U.S. Geol. Surv. No. 294,* p. 15.

[3] *Lancaster-Mineral Point Folio,* U.S. Geol. Surv., p. 2.

within these two quadrangles are not sufficient to determine whether the upper plain—that is, the one lying above the Niagara escarpment—is a peneplain or a structural plain, and its general history outside of these two quadrangles has not yet been completely worked out, though its age is probably Cretaceous." A plain probably to be correlated with the Niagaran plain was recognized and called the "Allamakee Peneplain" by Calvin[1] in his report on Allamakee County, Iowa. The intermediate plain has been referred to by Hershey as "Peneplain No. 2," and by Bain, and by Grant and Burchard as the "Lancaster Peneplain," and it has been assigned by them to the Tertiary period. Calvin and Leonard make no note of such a plain in the reports on Allamakee and Clayton counties in Iowa. The Cretaceous and Tertiary ages of these respective plains seem to have been tentatively established by their relation to Cretaceous deposits in Minnesota and Iowa, and to Tertiary deposits in the Gulf region. There is little or no evidence of the dates of formation of the plains in Jo Daviess County, and their ages do not form the problems of this paper.

It seems advisable here to describe and interpret these plains, as seen in Jo Daviess County, with a view to determining if there are any other possible explanations beside that of peneplains. The purpose of the discussion is twofold. First, it is hoped that it may lead to a true interpretation of these plains and an understanding of the physiographic history of the region in which they are found. Secondly, an attempt is made to bring out the criteria for distinguishing upland plains of certain origins and histories from those of other origins and histories. It is believed that criteria for distinguishing raised and partly eroded peneplains in regions of folded strata, such as the Appalachian Mountains, are fairly well worked out; but that many of these criteria will not apply in regions of horizontal or nearly horizontal structures, and that the characters of peneplains in such regions are not so well known as they should be and have not been given as critical study as they deserve.

THE NIAGARA PLAIN

In most places where the Niagara dolomite is found in Jo Daviess County, its top has an even skyline when seen from a distance and a flat surface as seen when it is traversed. It is always a hard

[1] *Geology of Allamakee County*, p. 43.

pull for a horse when one is driving up the upper slopes, but, once the top is reached, the road has little grade. This can be well seen on the upland over the Great Western tunnel, or on the hills around Elizabeth, or almost anywhere on the upland surface. Even in the north part of the district the Niagara-capped mounds are flat topped, and those which stand in east-west lines come up to almost a common level. It is clear that if all the valleys were filled up to the tops of the mounds, the resulting surface would be nearly flat, and the presumption is strong that there was once a plain here which has since been dissected. The mounds in the north part of the district reach elevations of 1,170, 1,152, 1,160, etc. In the central part, the mounds and the tops of the Niagara-capped ridges reach 1,112, 1,145, 1,065, 1,060, 1,072, etc. In the south portion of the district, considerable areas of the plain are found at 944, 964, 1,027, 1,004, and 1,000 feet. That is, if this plain were reconstructed, it would slope south and southwest about 175 feet in 16 miles, or about 11 feet to the mile. In Wisconsin, a few miles north of this district, this same surface on the Niagara dolomite reaches elevations of 1,400 feet, showing a continued rise in that direction. It is seen then that this plain, if reconstructed, would slope in the direction in which the rock strata dip and at about the same angle.

The origin of this plain is now in question. There are at least four possibilities: (1) it is an old peneplain uplifted and dissected after its formation by streams; (2) it is a plain made by a hard layer of rock at this stratigraphic horizon; (3) it is the original sea bottom which, after emerging, remained low and flat for a long time after the Niagaran epoch; or (4) it is the result of the erosive action of ocean waves cutting back on the land, at a time subsequent to the deposition of the Niagara dolomite and any other formations which may have been laid down on it, the present remnants resulting from the partial erosion of the surface by streams following uplift relative to the sea. The correct one or ones of these four hypotheses ought to be determinable by close field observation.

1. If such a flat is a dissected peneplain, (*a*) it is likely to have hills standing above it, which were left unreduced in the former cycle of erosion; (*b*) the surface is likely to have some relief; (*c*) the

thickness of the formation on which it is developed is likely to vary to a degree corresponding with the relief of the surface; (*d*) it is not likely to be parallel to underlying strata, but to rise or fall stratigraphically; (*e*) it would be expected to slope in the general direction, corresponding to the direction of flow of the streams that made it, unless tilting took place after its formation; (*f*) much of the plain might be covered with river detritus such as fine gravel, sand, and silt, similar to the materials of river-made plains today. If such a plain is not parallel to underlying strata, but lies across their beveled edges, particularly if the strata are known to have constant thicknesses where undisturbed, it is almost certainly a result of erosion going to a late stage—a peneplain. This might not hold if the strata were the result of near-shore deposition, and thinned out shoreward.

If the characteristics of the Niagara plain be compared with this set of features expected on a raised and partly dissected peneplain, they are found to correspond only in part. Concerning the plain as it is in these quadrangles, (*a*) no distinct hills stand above it; (*b*) the flat has little relief—probably no more than could have been given it by erosion following the uplift; (*c*) the thickness of the formation under it varies slightly but not greatly in short distances; (*d*) its surface does not rise or fall appreciably in the stratigraphic section, even when considerable distances are considered; (*e*) it does slope in a general direction and at about the angle expected for a peneplain; (*f*) no sand or gravel or stream alluvium were discovered on the flat, and it is certain that no great amount of such material was there and has been subsequently removed, for it is not found on the bordering slopes, and some of the plain has been unaltered by any agent which could remove the alluvium. From the foregoing, it is seen that this plain is not clearly a raised peneplain; neither is it surely not a peneplain. If traced beyond the limits of this region, and found there to go from Niagara to Maquoketa to the north and from Niagara to something younger to the south, it will have been proven, nevertheless, to be a peneplain.

2. In a second cycle of erosion, a flat of considerable magnitude might be formed on the top of a hard layer of rock, by the removal

of softer material from above, provided the streams were not able to cut through the hard formation for a long period of time. Such a plain would be essentially a peneplain, with the difference that its position is determined by a hard stratum, instead of by base level, and that it would require no uplift to start its dissection; dissection would result when the main stream had cut through the hard formation. It would have essentially the same characteristics as a true peneplain, with the marked exception that it would be parallel to the layers of rock, and remain at the same stratigraphic position over wide areas.

If the Niagara plain be tested by these criteria, again no definite conclusion can be drawn. As the flat is everywhere located on the Niagara, lies everywhere near the top of the massive member of that formation, and about 150 feet above its base, and as it has all the other characteristics of a true peneplain, it may be said to fit the second hypothesis better than the first.

3. Or is the Niagara plain the original surface which emerged from the sea at the end of the Niagaran epoch, and has suffered dissection since then? A surface having had such a history should have somewhat different characteristics from one developed in either of the ways previously outlined. (*a*) There would be no marked hills standing above the remnants of the plain, for there were no other strata above it from which hills could have been formed. (*b*) The thickness of the underlying formation would be expected to be uniform, except for possible differences in the amount of deposition on the bottom of the sea, or erosion since emergence from the sea. (*c*) The plain would have little or no relief, unless roughened after its emergence, by streams, wind, etc. (*d*) Like the plain developed on a hard layer, the surface would follow the rock structure, not rising or falling appreciably with reference to the strata. (*e*) Any slope the plain has would be the slope, in direction and amount, of the old sea bottom, unless tilting occurred during emergence or later. (*f*) No river detritus should be found on this surface, but instead material deposited at the shoreline as the shore receded over it, if anything. (*g*) In this case also, if the bottom of the old sea has been preserved as the plain, it might be expected that somewhere the old shorelines might be found as raised cliffs,

old beaches, etc., in places where protected from later erosion. (*h*) Marine fossils might be found on the surface of the plain.

Of these features the plain under discussion has some and lacks others. (*a*) It has no hills above it; (*b*) the underlying formation has a sufficiently uniform thickness to give the idea of an original plain; (*c*) the relief of the surface is sufficient but not too great; (*d*) the plain follows the structure fairly closely; the slope of the flat may be either that of the old sea bottom, or the result of slight subsequent tilting; (*f*) and (*h*) the materials of the surface afford no evidence, because there is a complete lack either of river detritus or of the shells of terrestrial or marine animals; (*g*) even if old shorelines were preserved at the edge of the ancient sea bottom, they would be found only at the margin of the plain, and this is outside the region under discussion. But no such shore features have been reported, and in all probability none exists. Even if the plain had had such a history as is here outlined, the factors mentioned in (*f*), (*g*), and (*h*) would not be expected to have persisted through such a lapse of time as the hypothesis presupposes.

4. There remains one other hypothesis to be analyzed and tested. If this plain is the result of marine erosion, it would have most of the characters of a peneplain due to stream erosion; that is, (*a*) it might have erosion remnants on its surface; (*b*) it might lie parallel with the strata in a general way, but it would be surprising if the two were exactly parallel; (*c*) it would slope in one general direction, in this case the slope being the oceanward slope of the old sea bottom; (*d*) some of the plain should be covered with marine sediments—debris deposited on the surface after its erosion, but before the recession of the sea. This plain would differ from a true peneplain in having little or no relief before dissection, and in having correspondingly little variation in thickness of the underlying formation within short distances. In addition, a plain so made must have been bounded originally by a shoreline of some sort, and this might or might not have been preserved, if the flat was preserved. Also, as the sea cut its way over the rock surface, and the flat off shore became wider and wider, the places eroded would gradually become sites of deposition, and this débris might

be found on the plain, either cemented into hard rock or uncemented.

Again the Niagara plain has some of these characters, but not all. So far as slope and the apparent original relief and the uniformity of thickness of the underlying formation are concerned, the plain might be explained along the lines of this hypothesis, but the correspondence of the surface with the structure of the beds, the absence of near-shore marine deposits, the absence of all shorelines, and the fact that no other large plains are known which seem to have been made in this way, would seem to point to some one of the other hypotheses as the true explanation of the flat.

Conclusion.—After this discussion it is apparent that the origin of the Niagara plain is from this region not perfectly clear, but that some speculation at least is warranted. The facts that the plain is so distinctly related to structure and that it shows no conclusive evidence of having been peneplained point toward the conclusion that it is the original plain or a structural plain (or both), rather than an old peneplain or a plain of marine erosion. It is unlikely that a peneplain would happen to be formed so closely parallel to structure as this flat is *over wide areas*. Still it is possible that, when traced into other regions, this parallelism will fail, and the flat will be proven to be a peneplain. It has been so long since the Niagaran epoch, that it appears extremely unlikely that a flat emerging from the sea at that time could have remained undestroyed until now, unless perhaps it be conceived that the surface took a position very near to sea-level from the start, and held that position until uplifted in relatively recent times. Perhaps it is a combination of a true peneplain and a structural plain, the flat having been developed on the hard Niagara dolomite at a level which was near grade for the streams of the region at that time. Possibly the flat is an original marine plain and also a structural plain, the last deposit in the sea having been made into hard rock (the massive Niagara). Most likely the plain under discussion is an ordinary structural plain, the surface having been developed due entirely to the hard Niagaran dolomite which held up the streams at that level until all overlying strata were removed, before the dolomite formation was finally cut through and dissection of the plain began.

THE GALENA PLAIN

The Galena plain is best developed and distributed over widest areas and can be seen to best advantage in the district around the towns of Scales Mound, Apple River, Warren, and Stockton. Here is a surface 150 feet lower than the tops of the mounds and ridges of the Niagara plain, and 150–200 feet above the stream beds. Except for the elevations above it and the depressions below it, the plain forms a wide area of slight relief. In Section 8, Rush Township, where its surface has not been modified, it has a relief of less than 20 feet for a whole mile. This is a little more flat than the average, but not greatly so. This plain is practically confined to the northern two-thirds of the county; it does not appear to any appreciable extent in the southern one-third, and is lacking entirely along the south edge of the Galena and Elizabeth quadrangles. In the vicinity of Galena it appears in flattish or rounded divides midway between the upland mounds and the valley bottoms. By close observation, similar features may be seen about as far south as the Great Western tunnel in the Galena quadrangle, and to about the latitude of Stockton in the Elizabeth quadrangle. If reconstructed, this plain also would slope southward at a low angle.

Stratigraphically, the Galena plain is located on the hard Galena dolomite or only slightly above it in the Maquoketa shale. The broad flat in the district around Scales Mound, Apple River, Warren, and Stockton is underlain directly by the upper thin beds of Galena, or locally far from the main streams by 5–15 feet of Maquoketa shale above the Galena. The rounded divides and narrow flats around Galena and north and south of that place are underlain by Maquoketa shale of thicknesses up to 30 feet. In the south part of the county where the Galena dolomite dips beneath the surface, the flat cannot be seen.

In the case of the Galena plain, only three of the four above-discussed means of origin are possible. It cannot be an original marine plain of deposition, because the mounds and ridges of Niagara dolomite stand above it, and have been made by processes of degradation since the recession of the sea. It may, however, be a structural plain on the hard Galena dolomite, or it may represent the beginnings of a true peneplain, or perhaps it is conceivable that it was carved out from the shale and dolomite above the Galena

by the waves of a slowly advancing sea. In either of the first two cases, streams were the agents of its formation, the cause of the flat only being different. If a structural plain, the flat was developed by streams, because they flowed down the dip of the top of the hard dolomite, scouring off the softer shale. If the flat is a remnant of a true peneplain in its beginnings, it was developed by streams because they had reached grade, and the region had been developed to an early peneplain stage before uplift allowed dissection in another cycle of erosion.

After analysis of the various features of this plain, the idea of marine erosion seems to be untenable. On such an extensive plain, marine near-shore deposits would have been sure to be deposited, and no suggestions of such deposits are found on the surface. Under this hypothesis, also, the mounds and ridges standing on the plain must have been islands, headlands, peninsulas, etc., and their sides must have suffered erosion by the waves which made the plain; that is, their sides must be shorelines of erosion. As most of these elevations stand out boldly on the plain, far from the main streams and valleys of the present cycle of erosion, it must be considered that they are about as they were left by the agent or agents which made them. This being the case, evidence of the work of waves on their sides should be visible now. But in contrast to this, the slopes of these mounds and ridges show every evidence of stream work, and have very clearly not been eroded to their present shape by waves; especially is this true in the central and southern parts of the county where the uplands form the stream divides and have the dendritic arrangement characteristic of topographies developed by the work of streams.

The Galena plain has all the main earmarks of an incipient peneplain after uplift and partial dissection, except that it follows the Galena dolomite with surprising closeness: (1) it consists of extensive flat areas lying between uplands and lowlands, and in such positions flat areas are not developed except for some special reason; (2) aside from recent dissection, it has about the flatness to be expected on a peneplain; (3) distinct erosional hills stand above it; (4) it slopes gently in the direction in which the present streams flow; but (5) it follows the top of the Galena formation

rather closely, and seems to disappear where that formation dips beneath the surface. However, close study of stratigraphy in connection with this flat shows the coincidence of flat and structure to be not so striking after all. In southwestern Wisconsin, Grant and Burchard[1] find evidence of a dissected peneplain on the upper part of the Galena formation, which now has an altitude of 1,000–1,100 feet. In the northern part of Jo Daviess County this surface is above a few feet of Maquoketa, and the shale formation gets slightly thicker under the flat to the south. That is, to a small degree the flat does lie across the beveled edges of different formations. These relationships are shown in Fig. 1. The Galena plain is believed by the writer to have been a true but only partly developed peneplain, but one somewhat controlled by rock structure.

The feature which seems at first to militate against the peneplain interpretation is the disappearance of the flat where the Galena dolomite dips below the surface. However, this may be explained. If the peneplain was developed on the Galena and Maquoketa formations as shown in the diagram (Fig. 1), the Maquoketa shale was thickest under the southern part of the plain. When the plain was uplifted and the streams were rejuvenated, the shale was attacked most vigorously downstream. The shale being soft, its dissection resulted in speedy destruction of the plain where the shale was thick; where lacking, the plain was preserved longer. Even where there was a little shale under the plain the main streams cut through it rapidly, and then were held to slow cutting by the hard Galena dolomite. Working in the hard rock, they did not send out tributaries as readily as they did in the soft shale farther south, and the flat was protected. It is believed then that the plain is a partly developed peneplain, the southern part of which, after uplift, has been destroyed because the shale which underlay this part was exposed and not resistant to erosion. The plain is more distinct in the central part of the district, and in the northern part it is very well preserved, because of the hard dolomite near or directly under it. Possibly also the dolomite had some influence in the development of the plain as well as in its modification.

[1] *Lancaster-Mineral Point Folio*, U.S. Geol. Surv., p. 2.

CONCLUSIONS

The mounds and ridges in Jo Daviess County, Illinois, are remnants of a plain which is either an old peneplain or a structural plain, and in the mind of the writer the latter interpretation is more likely to be correct than the former. It is probable that the district remained under the sea for some time following the deposition of the Niagaran rocks now found here, and that emergence took place some time after the Niagaran epoch. The region was then subjected to erosion, and a broad plain was developed on the hard Niagara dolomite. Finally this formation was cut through by the major streams, and the Maquoketa shale underlying was rapidly removed. The streams reached grade at the level now represented by the Galena plain, which in this district happened to lie in the upper part of the Galena formation and the lower part of the Maquoketa shale. Before the mounds and ridges on this plain had been brought low, probably in Tertiary time, an uplift occurred and the streams were again allowed to deepen their valleys in the old plain.

It is realized that a close study of these plains over wide areas will be necessary before a complete understanding of them is obtained. The whole driftless area seems to be the field of work. The writer hopes to do something more toward the solution of the problem at a later date.

THE SKULLS OF ARAEOSCELIS AND CASEA, PERMIAN REPTILES

S. W. WILLISTON
University of Chicago

There are few Permian reptiles of greater interest at the present time than the peculiar one I briefly described in this journal[1] three years ago as *Araeoscelis gracilis*. At the time of the description the material in the University collections had not been prepared, and it was in the hope of acquiring additional material from the Craddock bone-bed near Seymour, Texas, whence the type specimens came, that I have delayed the publication of further details concerning the genus. Unfortunately the bone-bed seems to be exhausted, at least so far as *Araeoscelis* is concerned. The material of the University has now been worked up thoroughly by Mr. Miller, and is sufficient to reveal nearly all the details of the skeletal structure of this strange reptile, which in many ways departs widely from all other known reptiles of the Texas deposits. The object of the present paper is to describe briefly the structure of the skull for the information of others working on allied material. The full description of the skeleton, with illustrations, will be published later.

The skull, as shown in the accompanying figures, will not require a detailed description at this time. Suffice it to say that the structure of the temporal region is determined positively, save perhaps the precise union of the squamosal and jugal. The absence or vestigial condition of the lacrimal I am also confident about. The skull in life may have been slightly narrower than is shown in the figure; I do not think it could have been wider.

It has been suggested, especially by Huene, that *Araeoscelis* shows affinities with the lizards. The structure of the skull confirms this suggestion in a startling way. Really about all that seems necessary to convert *Araeoscelis* from a "theromorph" into a primitive squamate reptile is the reduction of the squamosal from

[1] *Journal of Geology*, XVIII, 587, October, 1910.

below and a greater mobility, or streptostyly, of the quadrate. Our specimens show a loose union of the squamosal with the quadrate, and it was the absence of the squamosal and postorbital in one specimen which induced me at first to believe that the whole temporal region was open. It is very possible that a like condition existed in *Varanosaurus* and that it may eventually be found to have a superior temporal vacuity only. I hope to decide this point by a study of additional material later.

I cannot be sure of the differentiation of the elements of the slender parietal arch, but I think it is very probable that it is formed

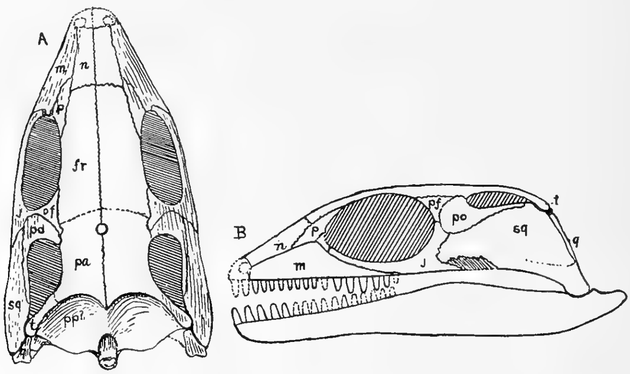

FIG. 1.—*Araeoscelis gracilis* Williston. *A*, skull, from above; *B*, the same from the side, both $\frac{3}{2}$ natural size; *fr*, frontal; *j*, jugal; *m*, maxilla; *n*, nasal; *p*, prefrontal; *pa*, parietal; *pf*, postfrontal; *po*, postorbital; *pp*, supraoccipital and paroccipital; *q*, quadrate; *sq*, squamosal; *t*, tabulare.

more or less by the tabulare, as in the Lacertilia. The exclusion of the postorbital from the orbit seemed almost incredible, but I am convinced that such was the case in *Araeoscelis* by the agreement of several specimens. This exclusion would seem to mean that the single bone found here in the Lacertilia and Mosasauria is really the fused two bones, the postfronto-orbital.

Whether or not *Araeoscelis* was phylogenetically related to the Squamata scarcely a doubt can remain that the single arch in lizards was the result of the progressive loss from below of the squamosal, and not the loss of the lower arcade in some rhynchocephalian reptile, as has been generally believed. The Squamata undoubtedly arose from just such a type of skull as is shown in *Araeoscelis*.

Broom[1] has recently expressed his belief that *Araeoscelis* is closely allied to *Bolosaurus*, a genus hitherto placed among the Cotylosauria by Cope, Case, and Huene, the type of a distinct family, the Bolosauridae. He has described a new genus from among the material in the American Museum which had hitherto been confounded with *Bolosaurus*, but of whose distinction from *Araeoscelis* he was not sure. So far as his descriptions and figures go (aside from the restorations), there is nothing to distinguish

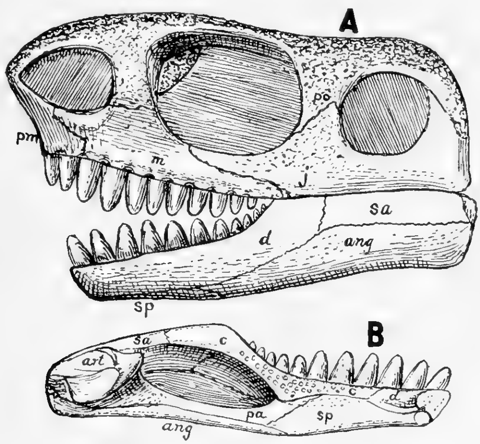

FIG. 2.—*Casea Broilii* Williston. *A*, skull from side; *B*, left mandible, both $\frac{3}{4}$ natural size; *art*, articular; *ang*, angular; *c*, coronoid; *d*, dentary; *m*, maxilla; *po*, postorbital; *pm*, premaxilla; *sp*, splenial.

Ophiodeirus from *Araeoscelis*, save perhaps in the teeth, in which I think he is in error. The teeth of *Araeoscelis* are simple throughout, without accessory cusps, and they are distinctly thecodont. There are, however, some differences in the teeth among the material which I have referred to *Araeoscelis*. Typically there are fourteen, or possibly fifteen, teeth in the maxilla, of the size I have shown in the figure. Another specimen, consisting of the maxilla and mandible only, has at least sixteen teeth in the maxilla, all of a uniform small size; yet another skull has fourteen teeth, all of nearly uniform size. *Bolosaurus* comes from the Wichita beds, doubtless

[1] *Bull. Amer. Mus. Nat. Hist.*, XXXII, 509, October, 1913.

of Carboniferous age; *Araeoscelis* from the Clear Fork, of Lower Permian age. Aside from the remarkable cuspidate and acrodont teeth, which are of more than generic importance, the structure of the skull in *Bolosaurus striatus*, as figured by Broom, separates the two genera into distinct orders.

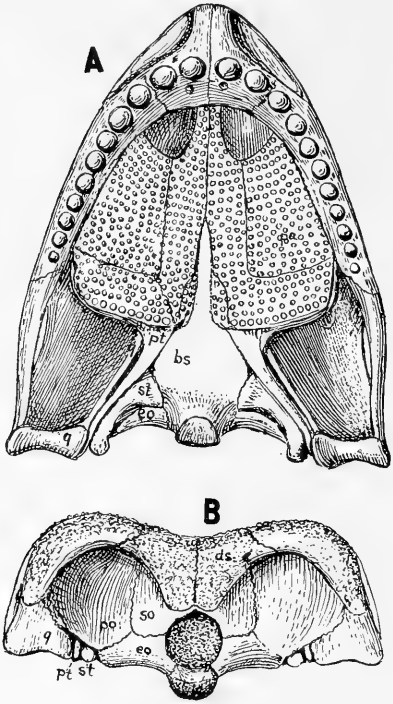

FIG. 3.—*Casea broilii*. *A*, skull from below; *B*, the same from behind; both $\frac{3}{4}$ natural size: *bs*, basi sphenoid; *eo*, exoccipital; *ds*, dermosupraoccipital?; *po*, paroccipital; *pt*, pterygoid; *pa*, palatine; *q*, quadrate; *st*, stapes.

A matter of more importance than the synonymy of *Ophiodeirus*, is the relationship of *Kadaliosaurus* Credner, from the Lower Permian of Germany. My attention to such possible relations was first called by a letter from Professor Jakolov written on the receipt of my paper containing the original description of *Araeoscelis*. He mentioned the fact that he had certain bones from Europe which seemed to be identical with those figured by me. A study of Credner's figures and description of *Kadaliosaurus* confirmed my belief of the affinity between the two genera, as I have already published. In showing our specimens to Dr. von Huene on his late visit to Chicago, I called his attention to these resemblances, in which he immediately concurred. Last April I had the privilege of studying the type specimens of *Kadaliosaurus* and *Paleohatteria* in Leipzig, for which my thanks are due to Professor Stille and Dr. Henkel. The material of *Kadaliosaurus* is imperfect, but, so far as it goes, I could not distinguish the genus from *Araeoscelis*, save by the greater size of the specimen and the presence of ventral ribs, both dubious characters.

It would of course be premature to say that *Kadaliosaurus* and *Araeoscelis* are congeneric, but I cannot resist the belief that they are closely allied at the least. Possibly here, as so often elsewhere, the conclusions based on negative evidence are unreliable. It is not at all improbable; indeed I think it very probable, that the isolation of the American Permian fauna, in which I have concurred, will eventually be shown to be much less than has been supposed.

As a postscript I may mention, that, notwithstanding the general accuracy of Credner's descriptions, his interpretation of the scapula and coracoid of *Paleohatteria* is quite wrong. The genus has a normal pectoral girdle, with the coracoid closely united to the scapula, and probably with the usual supracoracoid foramen. The scapula is rather short, perhaps an indication of subaquatic habits. As I have stated elsewhere, I could find no indication of a supratemporal vacuity in *Paleohatteria*, and much evidence that there was none. I may also add, that from an examination of the specimens of *Haptodus* in the Paris museum, kindly granted me by M. Thevenin, I am confident that the two genera are distinct. *Paleohatteria* has a distinctly rugose skull, while that of *Haptodus* is quite smooth.

VARIATIONS OF GLACIERS. XVIII[1]

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The following is a summary of the *Seventeenth Annual Report* of the International Committee on Glaciers.[2]

THE REPORT OF GLACIERS FOR 1911

Swiss Alps.—The general retreat of the glaciers in recent years was interrupted in the last two years by the advance of more than eight glaciers; but all of these glaciers have begun to retreat again. The remarkable heat of the summer of 1911 caused very great melting at the ends of the glaciers and seems to have brought their advance to an end.

Eastern Alps.—Here we have conditions very similar to those of the Swiss Alps. The hot summer of 1911 caused a very marked elevation of the snow line and the slight advance noted in 1910 was checked, and practically all the thirty-five glaciers under observation were in retreat. One only seemed to be stationary. The glaciers this year give no indication that the general retreat, which has been in progress for some time, has come to an end. The snow line is higher and the lower ends of the glaciers are flattened out by melting.

Italian Alps.—Observations at various points on the Italian side of the Alps show that, with one or two exceptions, the glaciers are continuing to retreat. On the south side of Mont Blanc the changes are very slight and the glacier in the Allée Blanche has actually advanced about eight meters.

French Alps.—In spite of the very hot summer of 1911 the glaciers on the French side of the Mont Blanc chain show a tendency to advance, and there is a distinct thickening of the glaciers a short distance above their ends. The glaciers of the Maurienne

[1] Earlier reports appeared in the *Journal of Geology*, III–XXI.

[2] *Zeitschrift für Gletscherkunde*, VII, 37–47, 191–202.

continue to retreat but very slowly. The great heat of the summer of 1911 does not appear to have greatly affected the glaciers in the northwestern part of the Pelvoux massif and in the Grandes Rousses. The general retreat has apparently been stopped in these mountains. The accumulation of snow has been increasing and this has protected glaciers from excessive melting.

Swedish Alps.—The Swedish glaciers lie pretty far north. Of the five under observation, four are advancing and one is stationary.

Norwegian Alps.—The interior glaciers of the Jotunheim are retreating; only two out of twenty-seven observed show slight advance. In the Folgefon and the Jostegalsbrae, near the west coast, thirteen glaciers are advancing and sixteen retreating. In the more northerly regions we find nine glaciers advancing and two retreating. It is rather interesting to note that different parts of the same glaciers are retreating at different rates.

Russia.—A number of glaciers in the Caucasus and several in the Altai Mountains are distinctly in a phase of retreat.

REPORT ON THE GLACIERS OF THE UNITED STATES FOR 1912[1]

In Colorado, the Hallet Glacier shows a trifling expansion (Mills). Although the snowfall during the winter and spring was very heavy, no change was apparent in the length of the Arapahoe Glacier (Henderson).

Mr. F. E. Matthes, who has been engaged in mapping Mount Rainier, sends me the following information regarding its glaciers:

> According to the testimony of Joseph Stampfler, a guide in the Mount Rainier National Park, who has lived since early boyhood at Longmire, in the valley of the Nisqually River, the Nisqually Glacier in 1885 extended to the point now occupied by the bridge on the government road to Paradise Park. The glacier accordingly has made a retreat of one thousand feet since 1885. In that distance it has left no marked morainal ridges, and the inference is that its retreat has been a fairly steady one.
>
> The retreat of the glaciers has been marked during the last four years (1909–12). The Paradise Glacier, which prior to 1909 descended from an irregular rock bench about 250 feet high to gather again on the flat terrace below (elevation 6,100 feet), now barely reaches the terrace in a few places.

[1] A synopsis of this report will appear in the *Eighteenth Annual Report* of the International Committee. The report on the glaciers of the United States for the year 1911 was given in *Jour. Geol.*, XXI, 423–26.

The ice cave in its front, formerly much visited by tourists, has disappeared. Joseph Stampfler states that the Paradise Glacier once covered the entire terrace to its very edge. He cannot fix the exact date when the glacier began to withdraw from the edge, but he knows that it must have been in the early eighties. This edge is now more than two thousand feet in front of the ice.

The névé line on the Cowlitz, Nisqually, Van Trump, Wilson, and Tahoma glaciers, situated on the southeast, south, and southwest flanks of the mountain, appears to lie normally at an altitude between 7,000 and 7,500 feet. During the abnormally dry summer of 1911 the névé line rose to 8,500 feet or higher. In certain places on the Paradise, Nisqually, and Van Trump glaciers old ice was exposed as high as 9,500 feet. On the Tahoma Glacier (southwest side) the ablation was less conspicuous.

Mr. Matthes has emphasized the fact that the summit of Mt. Rainier is not the principal reservoir of its glaciers, but that the cirques and even the flanks of the mountain collect more snow than the summit. This is due not only to their larger area but also to the fact that the snowfall reaches its maximum amount at a much lower altitude than the summit of the mountain.[1]

Professor Lawrence Martin sends me the following information regarding Alaskan glaciers:

Kenai Peninsula.—Spencer Glacier is said by A. W. Swanitz to be receding more rapidly than in 1911, on account of the artificial diversion of a glacial stream to the ice border.

Copper River.—The Allen Glacier, on the lower Copper River, upon whose stagnant, moraine-covered terminus the Copper River and Northwestern Railway runs for $5\frac{1}{2}$ miles, is reported by Caleb Corser to have commenced to advance during the summer of 1912. It was thicker and more crevassed than in 1911; and in places formerly covered by moraine, blue ice appeared. The northern margin is said to have advanced a half-mile. The largest glacial stream on the northern side of Allen Glacier has left its former channel for a new course a mile farther west. It has increased greatly in volume, and shifts frequently, causing much trouble to the railway on the northern alluvial fan of outwash gravels.

Heney and Grinnell glaciers were still advancing slowly in 1912. Childs Glacier (presumably the northern margin) advanced 60 feet between July 15 and September 30.

Miles Glacier seemed to be advancing farther into the frontal lake than in 1911. On August 16, 1912, a sudden flood (perhaps from the draining of a glacier-margin lake) swept down the Copper River from Miles Glacier, raising

[1] "The Undescribed Glacier of Mount Rainier," *The Mountaineer,* Seattle, V, 42–57; "The Glaciers of Mt. Rainier," *Appalachia,* XIII (1913), 24–27.

the water level 12 feet at Childs Glacier bridge, and doing much damage twenty miles farther south.[1]

Wrangell Mountains.—Kennicott Glacier was unchanged from 1911 to 1912; the descriptions of the upper portion of this glacier and its tributaries in 1911 and 1912 by Miss Dora Keen, who ascended Mount Blackburn in the latter year, indicate no significant present-day activity. Chitina Glacier is said by Benno Alexander to have advanced between 1911 and 1912.

St. Elias Range.—The previously unexplored glacier system of the St. Elias Range between Mts. Logan and Natazhat was partly mapped in 1912 by the American Boundary Survey party under D. W. Eaton. The Chitina Glacier, whose chief tributaries are Logan Glacier from the southeast and Anderson Glacier from the northwest, is $3\frac{1}{2}$ to 5 miles wide at the terminus. Logan Glacier is 45 or 50 miles long and $2\frac{1}{2}$ miles wide. It probably originates near Mt. Logan on a through glacier divide connecting with the Seward Glacier of the Malaspina system. The lower portions of Logan and Chitina glaciers are covered with ablation moraine and forest, including trees at least one hundred and ninety-three years old. The heavy growth of coniferous forest along the margins of Logan Glacier shows that it has not been larger than now for several centuries. The photographs and descriptions by Mr. Eaton show that Logan Glacier commenced a spasmodic advance in 1912 which widened and crevassed the upper portions of the glacier; ablation moraine material fell into crevasses; the glacier advanced over alders, and marginal lakes were formed. This activity after nearly two centuries of stagnation is probably the result of avalanches due to the earthquakes of September, 1899, in Yakutat Bay, which is less than 80 miles distant (only 50 miles from the divide between Logan and Seward glaciers). A small tributary of Anderson Glacier was also advancing actively in 1912.

Mr. C. G. Quillian, commanding the Unites States Coast and Geodetic Survey steamer "Mc Arthur," went close to the western edge of the Malaspina Glacier in May, 1911. He reports a new bay in the ice at the western edge of the glacier; its position indicates that the Guyot lobe of Malaspina Glacier has receded many miles. The new Coast Survey map (Chart 3002, March, 1912) indicates that this recession is about 9 miles, but Mr. Quillian's estimate is only $2\frac{1}{2}$ to $3\frac{1}{2}$ miles. The discharging face of the glacier within the bay was 200 to 250 feet high.

The writer of this review has concluded, from the study of a map and drawing made by Vancouver in 1794 and from a story handed down by the Yakutat natives, that the sea in the old Icy Bay of Vancouver reached to the Chaix Hills at the base of Mt. St. Elias in 1794. This involves the probability that the seacoast was subsequently pushed southward by the advance of Guyot

[1] For a detailed map of the lower Copper River glaciers see Lawrence Martin, "Gletscheruntersuchungen längs der Küste von Alaska," *Peterm. Mitt.*, LVIII, (1912, II), 78-81, 147-49.

Glacier, as was suggested in 1904 by Davidson. This advance of about 20 miles probably took place between 1847 and 1886. The ice front of the Guyot lobe practically maintained its advanced position at least from 1886 to 1909, and has since receded between 3 and 9 miles, forming a new Icy Bay, a little west of the old one. This results in the destruction of the Icy Cape salient of Guyot Glacier, one of the only two places where a tidal glacier entered the open waters of the Pacific Ocean.

The Canadian Boundary Survey party under N. J. Ogilvie found that Nunatak Glacier had receded about $\frac{1}{4}$ mile between 1911 and 1912.

Glacier Bay.—The same party measured a recession of $1\frac{6}{10}$ miles at Grand Pacific Glacier in Reid Inlet of Glacier Bay. This ice tongue receded at the rate of only about 1,500 feet a year in the twenty years before 1899. Since then it has retreated at the rate of over 4,300 feet a year from 1899 to 1906, 1,320 feet from 1906 to 1907, and approximately 3,300 feet a year from 1907 to 1911. Between September 2, 1911, when seen from a distance by the National Geographic Society's expedition under Tarr and Martin, and June 1, 1912, when visited and mapped by Ogilvie, this ice tongue retreated between $\frac{1}{4}$ and $\frac{3}{4}$ mile (according to accurate measurements by the Boundary Survey party, 14,520 feet in all from 1907 to June, 1912). In the two months from June 1 to August 1, 1912, there was a further unprecedented retreat of between one and $1\frac{4}{10}$ miles (5,000 to 7,425 feet). A portion of the terminus of Grand Pacific Glacier is now in British Columbia, so that the waters of Glacier Bay are partly Canadian. The following table summarizes the retreat of Grand Pacific Glacier:

Year	Amount, Feet	Rate per Year, Feet	Based on Observation by
1879–92	21,120	1,620	Muir, Reid
1892–94	2,500	1,250	Boundary Survey
1894–99	6,600	1,320	Gilbert and Gannett
1899–1906	30,360	4,337	F. E. and C. W. Wright
1906–7	1,320	1,320	Morse, Klotz
1907–11	13,200	3,300	Tarr and Martin
1911–12 (June)	1,320	7,320±	W. J. Ogilvie
1912 (June 1 to Aug. 1)	6,000±		

This recession of 15 to 16 miles in thirty-three years is unique. The acceleration of retreat immediately after the 1899 earthquakes may be only a coincidence, for the still greater acceleration of retreat since 1911 can be explained only by a marked deficiency in the snow supply, which may have begun years ago.

Arctic Alaska.—In the mountains north of the Yukon River small glaciers were discovered in 1911 by P. S. Smith[1] and by A. C. Maddren.

[1] P. S. Smith, "Glaciation in Northwestern Alaska," *Bull. Geol. Soc. Amer.*, XXIII (1912), 566.

A general description of the glaciation of the Alaska Range has been given by Capps[1] so far as it is known. The greater development of glaciers on the southern slope of the range, as compared with the nothern slope, is ascribed to the greater snowfall and to the larger collecting grounds. The southern slope is about twice as long as the northern.

Tarr has reviewed the observations made on Alaskan glaciers and their variations. He emphasizes the influence of avalanches due to earthquakes in causing spasmodic advance of glaciers.[2] In association with Martin he has published details of the sudden advance of the Yakutat glaciers due to the earthquake of 1899[3] (see earlier reports of this series). Grant and Higgins have collected their observations on the glaciers of Prince William Sound and Kenai Peninsula (already mentioned in these reports) in a bulletin of the United States Geological Survey, with maps and illustrations.[4] Several other bulletins of the Geological Survey contain maps showing the location of glaciers, but the descriptions of the glaciers are very cursory.[5]

[1] Stephen R. Capps, "Glaciation of the Alaska Range," *Jour. Geol.*, XX (1912), 415-537.

[2] Presidential address before the Association of American Geographers, *Science*, XXXV (1912), 241-258; and *Annals of the Assoc. of Amer. Geographers*, II (1912), 1-24.

[3] R. S. Tarr and Lawrence Martin, "The Earthquakes of Yakutat Bay, Alaska, in September 1899." *U.S. Geol. Survey, Prof. Paper No. 69*, chap. iv.

[4] *Bull. No. 526.*

[5] F. H. Moffit and Stephen R. Capps, "Mineral Resources of the Nizina District, Alaska," *Bull. No. 488;* Stephen R. Capps, "The Bonnifield Region, Alaska," *Bull. No. 501;* "The Yentna District, Alaska," *Bull. No. 534;* F. H. Moffit, "Headwater Regions of Gulkana and Susitna Rivers, Alaska," *Bull. No. 498.*

REVIEWS

"The Skeleton of *Ornithodesmus latidens*." By R. W. HOOLEY. In the *Quarterly Journal of the Geological Society*, LXIX (1913), 272–422; pls. XXVI–XL.

The present paper is of much interest and of importance in any discussion as to the relationships and structure of the pterodactyls. By diligent collecting Mr. Hooley has brought together a very considerable portion of the skeleton of a remarkable form hitherto known only doubtfully from fragments. *Ornithodesmus* is a pterodactyl of considerable size, more primitive in some respects than the American forms, but with certain peculiarities all its own. Its narial and antorbital vacuities are of enormous size; it has teeth in the front part of the jaws; a large keel on the sternum; a notarium and vertebral articulation of the scapula; doubtless a short tail; and no pubic opening.[1]

The femur Mr. Hooley describes as different from that of *Pteranodon* or *Nyctosaurus* in the divergence of the neck, but really there is no essential difference, the articular surface in all being at the extreme top, and its significance has already been discussed by the writer. Mr. Hooley believes that the wing metacarpal was shorter than the forearm; but that remains to be proved.

The pterodactyls offer a fertile field for speculation, and the author has availed himself of the opportunity presented by *Ornithodesmus* to propose a number of hypotheses as to the structure and habits of these strange reptiles, some of which are ingenuous, but the most of which seem doubtful to the present writer. He proposes an entirely new hypothesis as to the structure of the sternum, but one which is quite impossible of demonstration, if it be true, until the terrestrial ancestors of the pterosaurs have been discovered in Triassic rocks. He believes that the so-called manubrium, and the keel, whether large, as in *Ornithodesmus*, or small, as in *Pteranodon*, are really composed of the inter-

[1] While at Munich recently Dr. Stromer and the writer convinced themselves thoroughly of the presence of a true obturator foramen below the acetabulum, occupying its usual position in the early reptiles. Probably thorough search will reveal its presence in some form in all pterodactyls, definitely proving the fusion of pubis and ischium.

clavicle, to which the articulation of the coracoids has migrated and which is indistinguishably fused with the sternum proper.

The sternum is a comparatively late development in reptiles. In the primitive reptiles there was none, not even a cartilaginous one. The coracoids in all primitive reptiles met or nearly met in the middle line, underlain in their whole extent by the posterior prolongation of the interclavicle. Back of the coracoids, occupying the interval between their divergent hind borders and reaching to the pelvis, the under side was sheathed by ventral ribs in the majority of forms, leaving no space for even the smallest cartilaginous sternum. This condition has been found so often and in such perfect preservation among American Permo-Carboniferous reptiles that there can be no doubt of the entire absence of the sternum in all forms. Just what was the origin of the sternum, and the cause of its appearance, are of course yet unproven, but it seems to the writer extremely probable that the sternum is nothing more nor less than modified sternal ossifications in the parenchymatous tissue, of the same nature as the more posterior ribs and originally a part of the same series.

Evidence now seems conclusive that the plesiosaurs and ichthyosaurs are of very primitive origin, doubtless descended from terrestrial reptiles which had not yet acquired a sternum, and in which the coracoids met in the median line.

That the coracoids of the pterodactyls should have formed an articulation on the interclavicle in the absence of clavicles and the presence of an ossified or cartilaginous sternum is an improbable theory without any evidence that the writer can see to sustain it.

Mr. Hooley reaches some interesting conclusions as to the mechanics of the arm and forearm in *Ornithodesmus*, but which are not borne out by the American specimens of pterodactyls. He asserts that the radius, so far from its lying parallel with the ulna or in a pronated position, had acquired an over-supinated position, with its distal extremity on the dorsal side of the ulna. He also asserts that there was great freedom of movement in the carpus, not only dorsoventrally, but in an antero-posterior direction. With the arm extended and the elbow backward and the thumb in front, the humerus must necessarily occupy an oblique position or the radius is slightly pronated. With the radius crossing back of the ulna to the dorsal side, the palm of the hand would be turned forward. It is true that the wing metacarpal and the phalanges in their function of supporting the patagium have acquired an anomalous position in that the articulations have become antero-posterior instead

of dorsoventral; and doubtless this position has been acquired by a rotation on the carpus. But, to oversupinate the hand would turn the articulations anterior; and it seems very improbable. It may be added that the peculiar spiral position of the "deltoid" crest is a characteristic of all primitive reptiles.

As to the extreme freedom of movement in the carpus asserted by Mr. Hooley, one needs but to consult Dr. Eaton's excellent photographs of *Pteranodon* to be convinced of its impossibility, in that genus at least. That there was a considerable antero-posterior movement between the forearm and the wrist is not improbable, but that there was much movement dorsoventrally seems impossible.

As regards the classification of the Pterosauria, he makes some startling changes. He believes that most of the characters hitherto used, such as the shortening of the tail, the lengthening of the wing metacarpal, the development of a notarium and vertebral connection of the scapula, are all homoplastic characters, and the previous classification consequently an artificial one. He unites *Rhamphorhynchus* with *Pteranodon* in the Rhamphorhynchoidea; *Pterodactylus* he locates almost alone in the Pterodactyloidea; while for *Ornithodesmus*, *Dimorphodon*, etc., he makes a new sub-order, the Scaphognathoidea. And the grounds for this classification he finds almost exclusively in the degree of ossification of the facial part of the skull! Certainly there is more difference between *Rhamphorhynchus* and *Pteranodon* than between the latter and *Pterodactylus*, necessitating the resuscitation of Marsh's Pteranodontia. And then the next proposition doubtless will be to erect *Dimorphodon* into a sub-order all its own, till finally we shall have every genus a family and every family a sub-order! The writer disagrees with the proposed classification *in toto*.

S. W. Williston

Untersuchungen über die Bildungsverhältnisse der ozeanishen Salzablagerungen, in besondere des Stassfurter Salzlagers. By J. H. van't Hoff and Associates. Leipzig: Akademische Verlagsgesellschaft m. b. H., 1912. Pp. xix+374, figs. 39, pls. 8.

The now classic work of van't Hoff and his associates on the crystallization of salts from sea water first appeared in the *Sitzungsberichte der Kgl. Preus. Akad. der Wissenschaften*, and later, in two volumes published by Vieweg u. Sohn. Additions to the earlier work appeared

in various periodicals, some of which are not available to many readers. The desirability of making the work in its entirety more accessible has led to the publication of the present volume, which contains little or nothing that has not been previously published, but brings under one cover work that has hitherto been scattered through the literature of chemistry.

The first part of the book is devoted to simple compounds possible in sea water, with their hydrates, and solubilities, with particular reference to their phase-rule relationships with water. These are studied through a range including all reasonable temperatures of natural evaporation of sea water. Then more complex relationships, involving the equilibria between various combinations of these salts, their hydrates, and double salts, are studied with a rigorous application of the phase rule.

The methods of work are carefully outlined and the results are shown in diagrams that have been models for subsequent phase-rule studies for the past decade.

This monograph is a fitting memorial to the great chemist whom it commemorates and stands pre-eminently as an investigation carefully, thoroughly, and completely carried out—a finished piece of work.

A. D. BROKAW

Contributions to Economic Geology, 1910. Pt. I. Metals and Non-Metals except Fuels. By C. W. HAYES and W. LINDGREN. U.S. Geol. Survey Bull. No. 470. Pp. 558; figs. 64; pls. 17. Washington, 1911.

A collection of short papers and preliminary reports by various authors on investigations carried out during 1910.

The following papers are included:

Gold and silver: Trinity Basin, Cal.; Carson camp, Colo.; Upper St. Joe River Basin, Idaho; Ground Moraine in northwestern Montana; Elkhorn Mountains, Mont.; Ramsay, Talapoosa, and White Horse districts, Nev.; and Pinos Altos, N.M.

Copper: Burro Mountains, N.M.; Ducktown, Tenn.

Lead and zinc: Bear River Range, Idaho and Utah; Metaline District, Wash.

Rare metals: Arsenic deposits at Brinton, Vt.

Iron and manganese: Montevallo-Columbiana region, Ala.

Structural materials—building stone: Shelby County, Ala.; Granites of Massachusetts. Clays: Calhan, El Paso County, Colo.; Murphysboro quadrangle, Illinois; clays from Texas. Gypsum: Eagle County, Colo. Phosphates: Idaho Phosphate Reserve; Melrose, Mont.; western Wyoming. Mineral paints: paint shales of Pennsylvania. Sulphur: deposits near Soda Springs, Idaho. Miscellaneous non-metallic products: asbestos deposits in the United States; dolomite near Montevallo, Shelby County, Ala.; Graphite near Dillon, Mont.; fluor spar near Deming; N.M.

A bibliography of Survey publications on the subjects treated is found at the end of each chapter.

A. D. B.

Contributions to Economic Geology, 1910. Pt. II. Mineral Fuels. By M. R. Campbell. U.S. Geol. Survey Bull. No. 471. Pp. 663; figs. 15; pls. 62. Washington, 1912.

This bulletin is a collection of short papers by various authors on coal and oil fields investigated by the United States Geological Survey during 1910.

The reports cover the following regions, grouped by states:

Petroleum and natural gas.—Kentucky: Campton oil pool, Knox County. Alabama: Fayette gas field. Wyoming: Powder River oil field. Utah: San Juan oil field; Grand River. California: San Joaquin Valley.

Coal and lignite.—North Carolina: Dan River. North Dakota: Ft. Berthold Indian Reservation. Montana: Baker, Terry, Glendive, Sidney, Culberson, Milk River, Livingston, Trail Creek, and Electric fields. Wyoming: Little Powder River, Sussex, Lost Spring, and Wind River fields. Colorado: Gunnison Valley. New Mexico: Tigeras field. Utah: Deep Creek and Blacktail Mountain fields.

A table of miscellaneous analyses of coal samples from various fields of the United States is appended.

A. D. B.

Index to Volume XXI

Recent Publications

OF

The University of Chicago Press

Chicago and the Old Northwest, 1673–1835. By Milo Milton Quaife, Professor of History in the Lewis Institute of Technology.

488 pages, 8vo, cloth; $4.00, postpaid $4.23

This book recounts, in a manner at once scholarly and dramatic, the early history of Chicago. Important as this subject is, it is not treated solely for its own sake. The author's larger purpose has been to trace the evolution of the frontier from savagery to civilization. From the point of view of Chicago and the Northwest alone the work is local in character, although the locality concerned embraces five great states of the Union; in the larger sense its interest is as broad as America, for every foot of America has been at some time on the frontier of civilization.

This task has never before been performed in an adequate way. The one really brilliant historian of Illinois, Mr. Edward G. Mason, died with only a few fragments of his great work completed, and no one has yet come forward to take his place. It is believed that this book will take rank as the standard history of Chicago in the early days.

Chicago Tribune. A history of the beginnings of Chicago which, because it is scientific and based upon records rather than upon tradition, may overturn existing chronologies on the same subject.

Animal Communities in Temperate America. A Study in Animal Ecology. By Victor Ernest Shelford, Instructor in Zoölogy in the University of Chicago.

380 pages, 8vo, cloth; $3.00, postpaid $3.22

This volume by Dr. Shelford presents the principles of field ecology, illustrated by the more widely distributed animal habitats of the eastern half of temperate North America, and the aquatic habitats of a much larger territory. Six chapters deal with general principles.

In several chapters animal communities of lakes, streams, swamps, forests, prairies, and various soils and topographic situations are considered from the point of view of modern dynamic ecology. A very valuable feature of the book is the

three hundred figures of widely distributed animals chosen to represent the chief types of animal communities and their characteristic modes of life.

Artificial Parthenogenesis and Fertilization. By Jacques Loeb, Member of the Rockefeller Institute for Medical Research.

318 pages, 12mo, cloth; \$2.50, postpaid \$2.68

This new work presents the first complete treatment of the subject of artificial parthenogenesis in English. Professor Loeb published four years ago a book in German under the title *Die chemische Entwicklungserregung des tierischen Eies*. Mr. W. O. R. King, of the University of Leeds, England, translated the book into English, and the translation has been revised, enlarged, and brought up to date by Professor Loeb. It gives, as the author says in the preface, an account of the various methods by which unfertilized eggs can be caused to develop by physico-chemical means, and the conclusions which can be drawn from them concerning the mechanism by which the spermatozoon induces development. Since the problem of fertilization is intimately connected with so many different problems of physiology and pathology, the bearing of the facts recorded and discussed in the book goes beyond the special problem indicated by the title.

The Mechanistic Conception of Life. Biological Essays by Jacques Loeb, Member of the Rockefeller Institute for Medical Research.

238 pages, 12mo, cloth; \$1.50, postpaid \$1.65

The achievements of Professor Jacques Loeb in the field of experimental biology insure any book of his a wide reading. His experimental work at the universities of Chicago and California, as well as in his present position, gives this volume an especial significance. Professor Loeb here presents many of the current problems in biology, and discusses the question whether the phenomena of life can be unequivocally explained in physico-chemical terms.

Johns Hopkins Hospital Bulletin. All eager to know more of the origin of life will find no modern book of its size nearly so instructive or inspiring.

A Manual for Writers. By John M. Manly, Head of the Department of English in the University of Chicago, and John A. Powell, of the University of Chicago Press.

226 pages, 12mo, cloth; \$1.25, postpaid \$1.35

A book designed to aid authors and all others who are concerned with the writing of English. It aims to answer the practical questions that constantly arise in the preparation of

manuscripts for the printer, business letters, and any sort of composition where correctness of form is an important element.

It treats in a clear and convenient way the matters of grammar, spelling, and general form which writers need most to be informed about, and gives full directions on the preparation of "copy" for the printer and the correcting of proof. The chapter on letter-writing is unique and of especial value in its practical suggestions.

C. E. Raymond, Vice-President of the J. Walter Thompson Co. It seems to me to be the most comprehensive and comprehensible of any of the works on this subject which I have had the pleasure of seeing.

The Elements of Debating: A Manual for Use in High Schools and Academies. By Leverett S. Lyon, of the Joliet High School.

148 pages, 12mo, cloth; $1.00, postpaid $1.07

The aim of the book is to put the well-established principles of the art of debating within the reach of young students. It therefore presents the elements of public speaking so freed from technicality that the student may assimilate them in the shortest possible time and with the least possible interpretation by the teacher.

The book consists of ten chapters and a number of appendices. Each chapter is preceded by an analysis of the subject and followed by a series of suggested exercises. The whole subject is treated in a direct, practical way with the greatest possible clearness, and with illustrations drawn from subjects familiar and interesting to high-school boys. It is entirely modern in that it lays stress on efficiency, rather than on theoretical perfection. Illustrations are given from some of the most effective arguments ever written, and a list of suggested topics is added in an appendix.

London in English Literature. By Percy Holmes Boynton, Assistant Professor of English Literature in the University of Chicago.

358 pages, 8vo, cloth; $2.00, postpaid $2.17

This volume differs from all other volumes on London in that it gives a consecutive illustrated account of London not from the point of view of the antiquarian but from that of the inquiring student of English literary history.

It deals with ten consecutive periods, characterized in turn by the work and spirit of Chaucer, Shakespeare, Milton, Dryden, Addison, Johnson, Lamb, Dickens, and by the qualities of Vic-

torian and contemporary London. The emphasis is thus distributed over history and given largely to the richer and more recent literary periods. The temper of each epoch is discussed, and then in particular those literary works which are intimately related to certain localities in London.

The work contains four maps and forty-three other illustrations, selected from the best of a great fund of material. As further aids to the student or the general reader, the sources of all material are indicated by footnotes and lists of illustrative reading are appended to each chapter. There are also an appendix with detailed references to illustrative novels, and a carefully compiled index.

The Springfield Republican. It would seem as if Mr. Boynton's book would make strong appeal to everybody who has been in London, and a good many more who would like to go there; . . . . he has caught its spirit and presented it here.

Social Programmes in the West. (*The Barrows Lectures.*) *By Charles Richmond Henderson, Head of the Department of Practical Sociology in the University of Chicago.*

212 pages, 8vo, cloth; $1.25, postpaid $1.38

The Barrows Lectures (1912–13) delivered with so much success in the Far East by Professor Henderson are included in this volume, which is also published in India by the Macmillan Company. The subjects of the lectures are as follows: "Foundations of Social Programmes in Economic Facts and in Social Ideals," "Public and Private Relief of Dependents and Abnormals," "Policy of the Western World in Relation to the Anti-Social," "Public Health, Education, and Morality," "Movements to Improve the Economic and Cultural Situation of Wage-Earners," and "Providing for Progress." The author, in his preface, says that "the necessity of selecting elements from the social activities of Europe and America which might have value in the Orient under widely different conditions, compelled a consideration of the materials from a new point of view." The introduction includes, besides a syllabus of the six lectures, the Letter of Commission from the officers of the three great international associations for labor legislation, asking the lecturer to present their aims wherever it was possible in India, China, and Japan. There is also included a statement by Professor E. Fuster, of Paris, of the aims of the international associations on social legislation.

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FOR 1914

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